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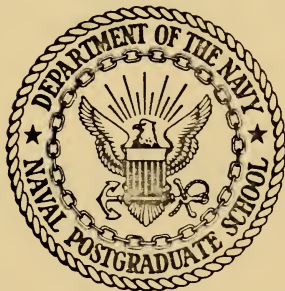
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A PROBABILISTIC EVENT-STEP COMPUTER SIMULA-
TION OF A REPAIRABLE ITEM INVENTORY
SYSTEM

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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

A PROBABILISTIC EVENT-STEP COMPUTER

SIMULATION OF A REPAIRABLE ITEM

INVENTORY SYSTEM

by

David John Quirk

Thesis Advisor: F. R. Richards

March 1972

A Probabilistic Event-Step Computer Simulation of a Repairable

Item Inventory System

by

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Lieutenant, S.C., United States Navy
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ABSTRACT

A probabilistic event-step computer simulation of a repairable item inventory system with exponential inner-arrival times between demands is constructed. The model allows for a wide variety of repair times and lead times to be considered. The major parameters are investigated for their sensitivity to system changes in order to help the user evaluate given or proposed inventory policies and parameters. A complete description of the model is presented and various measures of supply performance such as the expected number of unit years of backorders per unit period and the fill rate are provided. All flow charts and the GPSS/360 program listing are included.

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TABLE OF SYMBOLS AND ABBREVIATIONS

LFN — Location field name; a mnemonic symbol used to identify a particular program entity, section, or block in the simulation. Such names are primarily used for ease in programming and model identification.

XHj — Halfword savevalue j; j=1,2,3,...,100

A — XH72, instantaneous number of items on order.

ASO — Aviation Supply Office

B — XH71, instantaneous number of backorders.

BARB — XH96, the expected number of items on backorder at an arbitrary point in time multiplied by 100.

BKORD — Acronym for the Backorder Event

B_T — XH97, expected number of unit years of backorders, for 10 years of operation multiplied by 100.

$\hat{B}_T$ — Expected number of unit years of backorders, $(B_T/10)$.

BTCHZ — LFN for the table which stores the value of the size of each batch of items repaired.

BTIME — LFN for the table which stores the length of time each backorder is outstanding.

C — XH73, instantaneous number of items in repair department.

D — XH74, instantaneous number of items ready for issue.

DIFF 1 — XH90, difference between the simulated result for the average number of items on hand at an arbitrary point in time and the theoretical expression for the same quantity multiplied by 100.

DIFF 2 — XH89, difference between the expected number of unit years of backorders per unit period and the average number of backorders at an arbitrary point in time multiplied by 100.

ENOH — LFN for the table which stores the average number of items on hand for each random observation multiplied by 100.

F	XH77, cumulative number of demands satisfied without any time delay (the number of fills).
FASTR	LFN for the storage which represents the repair process for the infinite server queueing system.
FFCj	Function follower card j, j=1,2,3,4.
FILRT	XH69, fill rate times 10,000, i.e., 7356=73.56%.
FSTRQ	LFN for the queue which represents the entire repair department for the infinite server queueing system.
IP	XH70, instantaneous value for inventory position. IP=(D-B+C+A)
K	XH4, maximum batch size for single server queueing system.
L	XH3, minimum batch size for single server queueing system.
LBL	XH14, lower bound for uniform lead time distribution.
LBR	XH9, lower bound for uniform repair time distribution.
LFN	Location Field Name, a mnemonic symbol used to identify a particular program entity, section, or block in the model. Such names are primarily used for ease in programming and model identification.
M	XH79, cumulative number of demands in a unit period.
MOPj	Measure of Performance j, j=1,2,...,12.
NBARB	LFN for the table which stores the number of backorders for each random observation.
NUMC	LFN for the table which stores the number of items in the repair department for each random observation.
ORDER	Acronym for the Order Event.
P	(XH5/1000) Probability of a type 1 item (repairable item), i.e., XH5=0900=$\Rightarrow$P=.9
Q	XH1, reorder quantity.
R	XH2, reorder point.
RDYRT	LFN for the table which stores the value of XH44 for each random observation. XH44=10,000 if D$\rightarrow$0, 0 if D=0. Used in ready rate calculation.

SLOWR   LFN for the storage which represents the repair
process for the single server queueing system.
The simulated repair time.

SLOWQ   LFN for the queue which represents the repair
department for the single server queueing system.
The simulated time the item is in the repair
department.

SPCT   Acronym for the Inspection Event.

TYPE 1   A failed item which is repairable. Occurs with
probability P.

TYPE 2   A failed item which is not repairable. Occurs with
probability 1-P.

UBL   XH15, upper bound for uniform lead time distribution.

UBR   XH10, upper bound for uniform repair time distribution.

$\bar{X}$ Mean demand during repair time.

Y(j)   Function values for empirical lead time and repair
time distributions. $0 \le Y_j \le 1$, $j=1,2...10$

ACKNOWLEDGEMENT

I.   INTRODUCTION

Traditional inventory analysis is ultimately concerned with two decisions: (1) when to order and (2) how much to order. Most of the work done in the past addresses itself to these questions for non-repairable items (consumables). A thorough treatment of such inventory models for both the backorders and lost sales case for numerous resupply and demand distributions now exists.

However, at least in military applications, repairable items have now been found to be of great importance both materially and financially. Repairables often account for a significant portion of the items controlled by an activity and even more significantly when their portion of the total dollar investment is considered. For example, focus on one of the inventory control points of the U.S. Navy dealing with repairables such as the Aviation Supply Office (ASO) in Philadelphia, Pennsylvania. At fiscal year's end 1971 repairables represented 18.7% of the different types of line items controlled by this activity for a total of 66,000 separate items. These same items reflect an investment of nearly 3.1 billion dollars, almost 60% of ASO's total dollar investment. Further, ASO spends about 16 million dollars per month for repairs on these items and another 28 million dollars monthly for procurement of such items. Among ASO managed repairable items, 365,000 units were reworked in

fiscal year 1971. In view of the above figures it is easy to see why a need exists to help the manager improve his control over repairable items. It appears that an effective control over repairs would free for other needs many ASO dollars now spent on procurement.

Until fairly recently the control of repairable items had not received much attention. Even in the case of consumables there are major difficulties in applying inventory theory to the problem because of the intricate relationships of the involved item parameters, such as demand and lead times. Also the number of different types of line items complicates the task. The introduction of repairable items makes the problem even more difficult since repairable items often require special storage, handling, packaging and shipping procedures due to their complexity. In addition, the introduction of the extra source of supply, the repair department, causes further complications. On the other hand, repairable items tend to minimize the number of different type of line items needed to be carried by an activity; the parameters are usually more easily determined than those of consumables; and the procurement lead times are more reliable. In addition, upper bounds for the total demand can often be determined, for if a given repairable item is a subcomponent of a larger unit, the number of larger units in use is generally easy to determine.

Few people have addressed the problem of repairables. However, Schrady [Ref. 8] and others at the U.S. Naval

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Postgraduate School, as well as Feeney and Sherbrooke [Ref. 6], have looked at the problem for the deterministic case. Feeney's and Sherbrooke's model included the çapability of handling compound Poisson demands but without degradation of supply. Wilson and Richards [Ref. 10] extended this model to allow for this possibility. Due to problems of convexity and others, no one has come up with a quick and easy way to evaluate and compare alternative repairable item inventory systems on a larger scale. Richards [Ref. 7] addresses this problem and this paper supplements his work by providing a detailed simulation model along with a programming guide and flow charts. This model enables the user faced with such problems to easily come up with numerical values for various measures of performance such as the average number of back-orders per unit period or the average number of fills per unit period. These measures of performance can then be used by the manager to evaluate and compare alternative systems. Further, the model can also be used as a teaching aide to help students and/or supply personnel get a clearer understanding of the relationships between the various parameters involved in various inventory systems. A more detailed description of the model and how to use it are given in sections II, V, and VI of this paper.

II. THE MODEL

The model presented in this paper is a general event-step
computer simulation of the interactions between the major
parameters for Q R, continuous review inventory systems.
Here, Q is the order quantity and R is the reorder point for
a given system. The purpose of this general model is to test
and investigate the sensitivity of the parameters involved
to help the decision maker evaluate, modify, and/or set up
appropriate inventory systems. It is also used to demonstrate
the analytical results obtained by Richards [Ref. 7]. The
inventory systems simulated are single item, single echelon,
and repairable or non-repairable systems where failures are
assumed to be Poisson distributed. The model is a probabil-
istic simulation in that the success or failure of any
probabilistic event is determined in the model by comparing
the numerical value assigned to the probability of success
or failure to a program generated random number. In this
model the numbers so used are obtained from many different
distributions, using the one which best fits the particular
parameter being considered in each case. Further, it is an
event-step model in that the master program is controlled by
a subprogram called an event list which is repeatedly updated
as the master program switches from one event subroutine to
another. This eliminates the necessity to look at the status
of the entire system after each time unit (one hour) to
decide whether or not an event has occurred.

Figure 1 shows the general type of inventory systems addressed in this paper. In order to help the reader understand the relationships pictured there, the following definitions for the on-hand inventory, repair inventory, and others are given. Note that because of the addition of the repair facility, the commonly used definitions of the various states for the consumable item inventory system must be modified.

Definition 2.1: The on-hand inventory (D-B) includes all of the items ready for issue (D) less any backorders (B). Note that the on-hand inventory will be positive if there are no items on backorder.

Definition 2.2: The repair inventory (C) includes all items at the repair facility, including both those undergoing repair and those waiting to begin repair.

Definition 2.3: The net inventory (D-B+C) includes the on-hand inventory and the repair inventory.

Definition 2.4: The inventory position (D-B+C+A) is the sum of the net inventory plus all items which have been placed on order but have not yet been received.

Consider the inventory system as one which has control of a large number of items of a single type where the number of demands (failures) for any time period is a value of a random variable having a Poisson distribution with mean rate λ. The items which fail are assumed to be repairable with probability P and with probability (1-P) the items are scrapped. These failures will be referred to
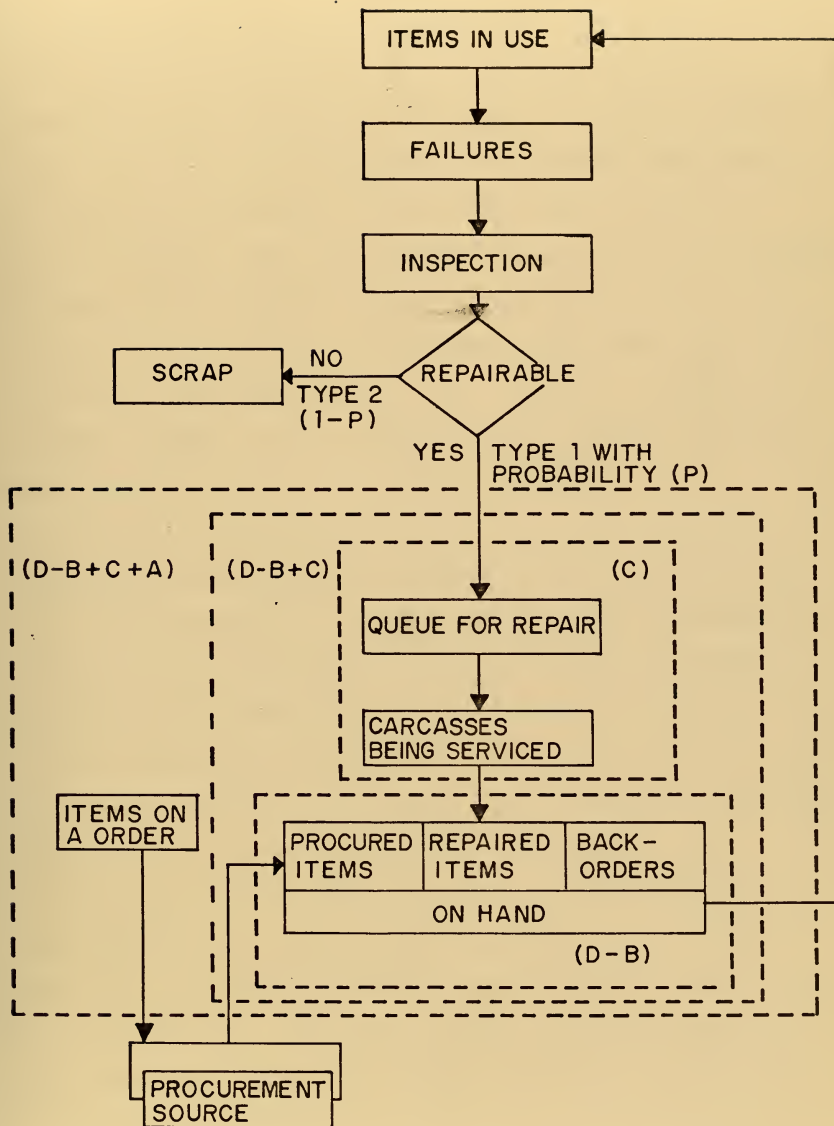
Figure I. Repairable item inventory system.

as type one and type two, respectively. The manager
controlling the system attempts to minimize the time
required to fill a demand by maintaining a stock of items
ready for issue. Systematically, the manager supplements
his stock by procurement of new items and/or receipt of
repaired items. Hence the manager is faced with the problems
of when and how much to reorder. Standard approaches try
to answer these questions by concentrating their efforts on
minimizing the total expected cost. However, a difficulty
in this approach is the determination of proper weights to
assign to the various cost factors involved.

A second approach concentrates on a class of simple
procurement policies based on one or two parameters. The
goal of this approach is to describe the long-term effect
of an arbitrary member of the class of simple procurement
policies being considered and then determine the choices
for the corresponding parameters which are best with respect
to a given measure of performance. This computer simulation
allows the user to do this quickly and easily.

After a class of simple policies has been specified,
the study of the inventory model becomes a study of the
associated stochastic processes and the long run properties
of the processes.   Emphasis is given to determination of
stationary distributions which describe the probabilities
of being in the various states after the system has been in
operation for a long period of time. This computer program
greatly simplifies the procedure whereby actual numbers are
produced for these various entities.

The program is capable of representing the repair department in one of two ways. First, as an infinite-server queue with general independent repair times which can be constant or realizations of a uniform, normal, or empirical distribution. Under this policy the repair department acts as a M/G/∞ queueing system which for the random repair times case will allow crossing of repair times. The crossing of orders is also allowed in this case.

The second method considers the repair department as a single server queueing system. That is, only one batch of items up to a maximum quanitity (K) can be repaired at one time. Under this policy the user also has the option to enforce a constraint on the minimum batch size (L) as well. This latter policy is provided because frequently in the case of repair, large set-up costs, tool-up costs, or manpower constraints make the second repair policy more economical.

III. EXPERIMENTS

A. OBJECTIVES AND APPROACH

   1. Objectives

      The objectives of this paper are threefold. (1) To
show the need for and justification of such a simulation.
(2) To demonstrate the analytical results obtained by
Richards [Ref. 7]. (3) To provide a means through which a
decision maker can evaluate given or hypothetical inventory
systems.

      The first objective has been touched on already and
will be complemented by the rest of this paper. Consistent
with the second and third objectives, a number of experiments
were performed which involved generating operating statistics
in order to quantitatively compare the simulated results to
the theoretical and display the sensitivity of various
parameters for particular systems.

   2. Approach

      Each experiment consisted of a series of simulation
runs. Each run simulated up to 14 unit periods, where a
unit period represented ten years of actual operation of a
given inventory system. For each run, operating statistics
were collected for all measures of performance listed in
Table I. For illustration purposes two measures of per-
formance were chosen to judge the performance of the hypo-
thetical systems examined in this paper. Those chosen were

TABLE I. SUPPLY PERFORMANCE MEASURES

MOP 1 (F)   = XH100: The average number of fills in a
                 unit period.

MOP 2 (FILRT) = XH99 : The fill rate multiplied by 100.
                 This is the probability of being able to satisfy a
                 demand without a time delay.

MOP 3 (B)   = XH98 : The average number of backorders
                 incurred in a unit period.

MOP 4 (B_T) = XH97 : The expected number of unit years
                 of backorders in a unit period multiplied by 100.

MOP 5 (BARB) = XH96 : The average number of items on
                 backorder at an arbitrary point in time multiplied
                 by 100.

MOP 6 (RDYRT) = XH95 : The probability of being able to
                 fill a demand at an arbitrary point in time multi-
                 plied by 100.

MOP 7 (ENOH) = XH94 : The average number of items on
                 hand at an arbitrary point in time multiplied by 100.

MOP 8 (ORD)   = XH93 : The average number of orders
                 placed in a unit period.

MOP 9 (RI)   = XH92 : The average number of repair
                 inductions (batches of items repaired) per unit
                 period. In the infinite server queueing system
                 RI will be C.

MOP 10 (C)   = XH91 : The average number of items in
                 the repair department at an arbitrary point in time
                 multiplied by 100.

MOP 11 (DIFF 1) = XH90 : The difference between ENOH and
                 the theoretical value (V4) of the expected number of
                 items on hand at an arbitrary point in time multi-
                 plied by 100.

MOP 12 (DIFF 2) = XH89 : The difference between B_T and
                 BARB multiplied by 100. This is calculated to
                 illustrate that the total time-weighted backorders
                 incurred in a unit period is equivalent to the
                 expected number of backorders at an arbitrary point
                 in time.

NOTE: Measure of performance four (B_T) would normally be normalized $(\hat{B}_T)$ by dividing by ten, i.e., XH97=1102= $(\hat{B}_T)$=1.102.

the expected number of unit years of backorders and the average number of items on hand at an arbitrary point in time. For all runs the system was preloaded such that the inventory position was equal to the sum of the order quantity and reorder point. It was felt that this would result in negligible transient times, hence the entire run's statistics were usable in all cases. The input values of all parameters, for what was called the parent system, are summarized in Table II. Deviations from these values of the parent system for any one experiment are pointed out in the description of each experiment as well as in Table III.

TABLE II. PARENT SYSTEM PARAMETER VALUES

PARAMETER	VALUE
Order quantity (Q)	=10
Reorder point (R)	=0,1,2,3...
Minimum batch size (L)	=0
Maximum batch size (K)	=0
Probability of repair (P)	=.9
Mean demand during repair time $(\overline{X})$	=1.4
Type of distribution for repair time	-constant
Mean repair time $(\overline{X}_R)$	=336 hours
Lower bound for uniform repair time (LBR)	=0
Upper bound for uniform repair time (UBR)	=0
Variance for repair time distribution (σ_R)	=0

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Type of distribution for lead time          -constant
Mean lead time ($\overline{X}_L$)                       =504
Lower bound for uniform lead time (LBL)     =0
Upper bound for uniform lead time (UBR)     =0
Variance for lead time distribution ($\sigma_L$)  =0
Type of output desired                      -summary
```

TABLE III. CHANGES TO PARENT SYSTEM PARAMETER VALUES

A. CHANGES FOR EXPERIMENT ONE

  (Q)=1,2,3,...,10 $(\overline{X})$=1.4, 2.75, 4, 5.5

B. CHANGES FOR EXPERIMENT TWO

  Type of distribution for repair time--constant,
                                        uniform, normal,
                                        and empirical

  Type of distribution for lead time --constant,
                                        uniform, normal,
                                        and empirical

  LBR=168 hours   LBL=240

  UBR=504 hours   UBL=768

  σ_R = 75 hours σ_L =116

C. CHANGES FOR EXPERIMENT THREE

  (Q)=2   (K)=1, 2, 3, 4, 5, 6   (L)=1

D. CHANGES FOR EXPERIMENT FOUR

  (Q)=2   (L)=1, 2, 3, 4   (K)=4

E. CHANGES FOR EXPERIMENT FIVE

  (Q)=2   (K)=4   (L)=1

  $(\overline{X})$=0.40, 0.65, 0.75, 0.80, 0.90, 1.15, 1.40

B. DESCRIPTION OF EXPERIMENTS

   1. First Experiment: The Whole Spectrum

        The first experiment considered the parent system
but with values of mean demand during repair time of 1.4,
2.75, 4, and 5.5. Also, order quantities of one through
ten and variable reorder points were allowed. That is, for
each combination of demand and order quantity above, the
reorder point (R) was allowed to vary from an initial value
of zero until the expected number of unit years of backorders
reached an acceptable stationary level. This was done in
order to see how the measures of performance, particularly
the two mentioned above, varied with respect to changes in
the order quantity and reorder point for the system described
above.

        The amount of computer time required to run one period
ranged from a low value of 5.89 seconds for $(\overline{X})$=1.4, with
Q=10 and R=7; to a high value of 28.57 seconds for $(\overline{X})$=5.5,
with Q=1, and R=0. The total computer time required for
this experiment would obviously depend on the particular
inventory system being investigated by the user. It is
assumed that the user would know, determine, or estimate
his system demand such that he could restrict his investiga-
tion to one or two values. Therefore, the number of runs
and total computer time required for his experiments would
be significantly less than that required for these presented
in this paper. Some typical results of the first experiment
are shown in Figures 2 and 3.

FIGURE 2

TYPICAL RESULTS OF EXPERIMENT ONE
REORDER POINT (R) VS UNIT YRS. OF BACKORDERS (B_T)
PER UNIT PERIOD

WHERE: $\overline{X} = 5.5$

Q = 1 ▼   Q = 6 ▲
Q = 3 ▶   Q = 9 ◀

B_T

R

FIGURE 3

TYPICAL RESULTS OF EXPERIMENT ONE

REORDER POINT (R) VS. UNIT YRS. OF BACKORDERS (B_T) PER UNIT PERIOD

WHERE: $Q = 2$

$\bar{X} = 5.5$ ▼ $\bar{X} = 2.75$ ▲
$\bar{X} = 4.0$ ▼ $\bar{X} = 1.40$ ▲

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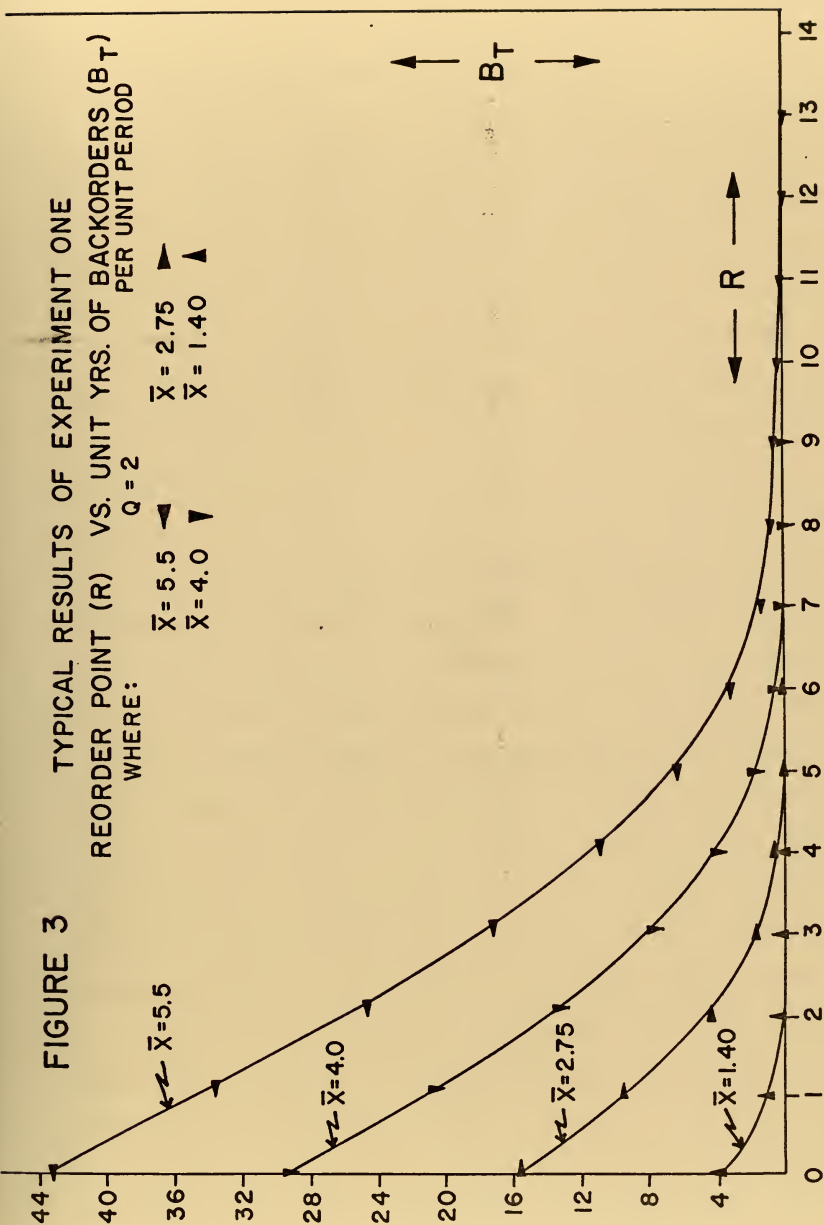
2. Second Experiment: Distribution Test

For this experiment a representative system from experiment one was chosen for further study. The system chosen was thought to be a typical, low demand, high cost, repairable item inventory system with a reorder quantity of ten and a mean demand during repair time of 5.5. The particular reorder quantity used is a somewhat subjective choice which the manager would make. Hopefully the manager could look at the results of experiment one and pick what would be the best quantity. A procedure to do this is explained in the analysis of experiment one. However, what will often happen is that one of several possible factors will force the manager to live with some predetermined order level. Some examples of these may be: there is a minimum number of items that the manager can let a contract for with a particular manufacturer, or an engineering requirement forces items to be procured in matched pairs or sets, or possibly a fixed unit of issue by the manufacturer. Regardless of how it is decided upon, once the reorder quantity is fixed the sensitivity of the system can be investigated by changing various input factors such as the repair time distribution or lead time distribution, as was done in this experiment. Constant, uniform, normal, and empirical repair and lead time distributions were examined. For each combination of distributions the reorder point (R) was varied until the total unit years of backorders was stationary. The purpose of this experiment was to show the sensitivity or

FIGURE 4   TYPICAL RESULTS OF EXPERIMENT TWO
REORDER POINT (R) VS. UNIT YRS. OF BACKORDERS (B_T)
WHERE: $\bar{X} = 5.5$ $Q = 10$ PER UNIT PERIOD

EMPIRICAL DISTRIBUTION
UNIFORM DISTRIBUTION
CONSTANT DISTRIBUTION
NORMAL DISTRIBUTION
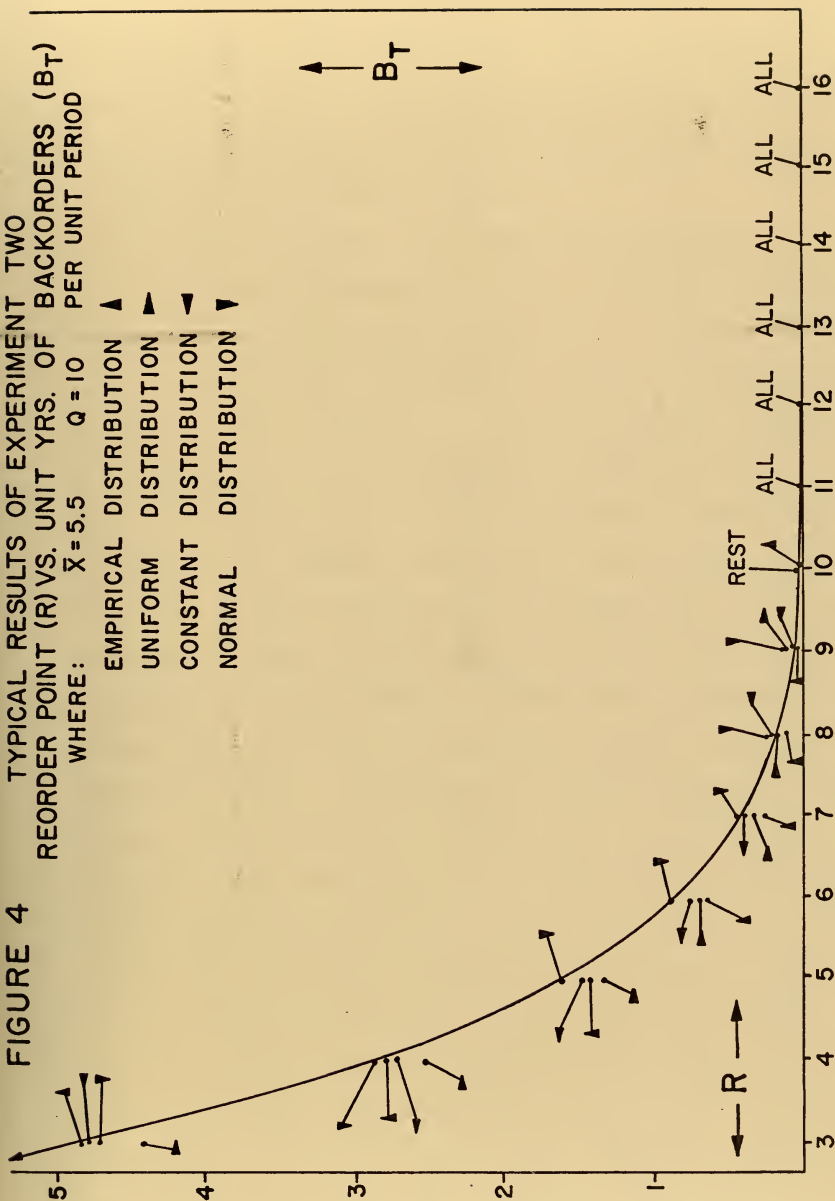
insensitivity of the modified parent system to various types of distributions for the repair and lead times each having the same mean and variance. Some typical results of the experiment are given in Figure 4.

   3.   Third experiment: Maximum Batch Size Test

       For this experiment the parent system was modified in order to treat the repair department as a single server queueing system where the server is capable of handling as many as K items at one time. Using the procedure explained in the analysis of experiment one, the order quantity was fixed at a value of two for this experiment. Then the sensitivity of the reorder point (R) was investigated by varying R for each feasible value of K, the maximum batch size, until the expected number of unit years of backorders reached an acceptable stationary level. A simple way to determine the maximum value for K is to look at the results obtained in experiment one for the comparable infinite server queueing system. The run in experiment one where all the input parameter values were identical to this one with the exception of the parameters associated with the repair discipline would be the comparable infinite server queueing system. One of the items included in the summary output for Storage Statistics, FASTR, summarizes the statistics for the case in which the repair department is treated as an infinite server queue. Two of the particular statistics included there are the average number of items in the repair department and the maximum number of items that were ever in the

FIGURE 5

TYPICAL RESULTS OF EXPERIMENT THREE
REORDER POINT (R) VS. UNIT YRS. OF BACKORDERS (B_T)
WHERE: $\bar{X}=1.4$ $Q=2$ PER UNIT PERIOD
MAXIMUM REPAIR BATCH SIZE (K) IS:

K = 2
K = 3
K = 4,5,6
K = 1

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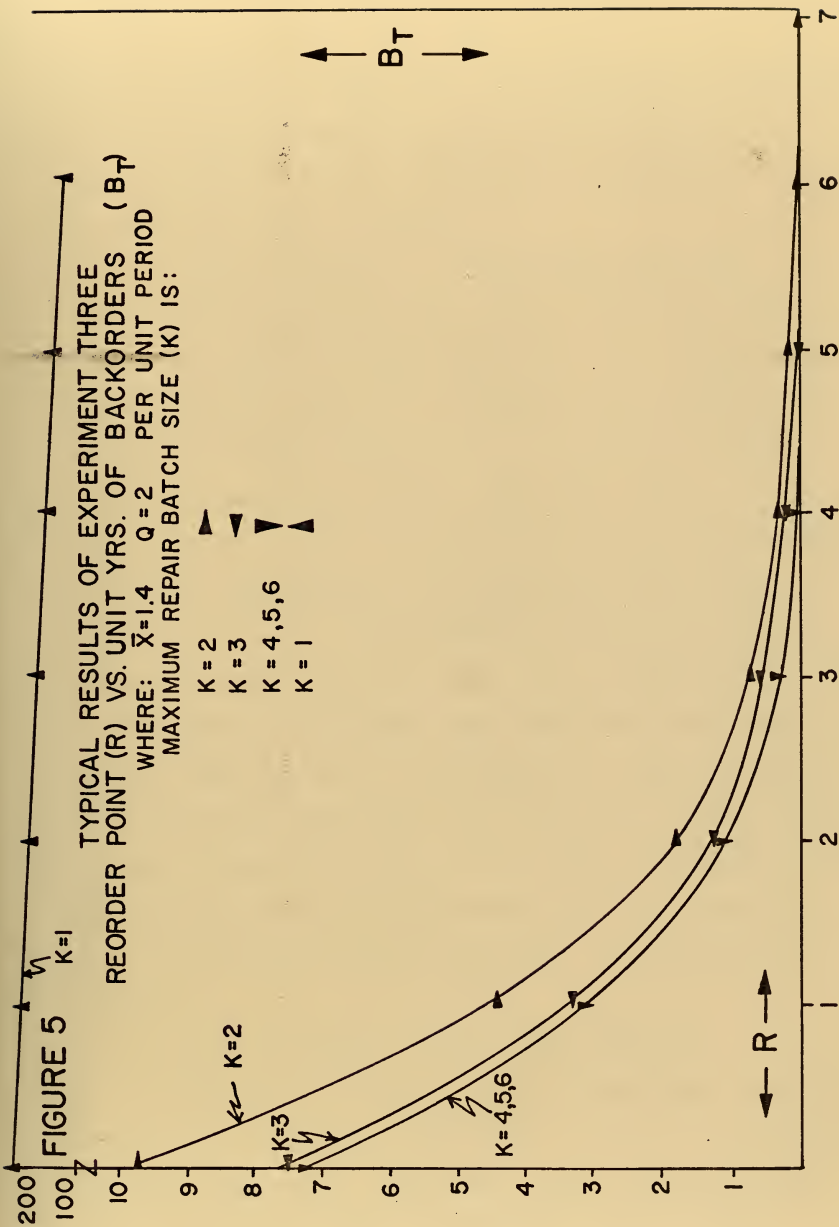
repair department at any time. These particular values were used in this experiment as a guide for determining the maximum value for K to be considered. The results of this experiment are shown in Figure 5.

4. Fourth experiment: Minimum Batch Size Test

In this experiment the parent system was again modified to treat the repair department as a single server queueing system. Again, as in the last experiment, the sensitivity of the reorder point to the type of repair policy used was investigated. This time, however, K rather than L was held constant while R was varied for each value of L, the minimum batch size, until the expected number of unit years of backorders reached an acceptable stationary level. The values of L were varied from one to K. The value of K used was four, which was the maximum feasible quantity for K as determined by experiment three. Since the repair department was treated as a single server queueing system, the repair of one batch of items must be completed before repairs can begin on the next batch of items. The results of this experiment are presented in Figure 6.

5. Fifth Experiment: Mean Repair Time Test

The modified parent system of experiment four was used for this experiment but with L=1 and with various mean demands during repair time $(\overline{X})$. The mean demand during repair time was allowed to vary from 1.40 to 0.40 by changing the mean time to repair from 336 hours to 96 hours
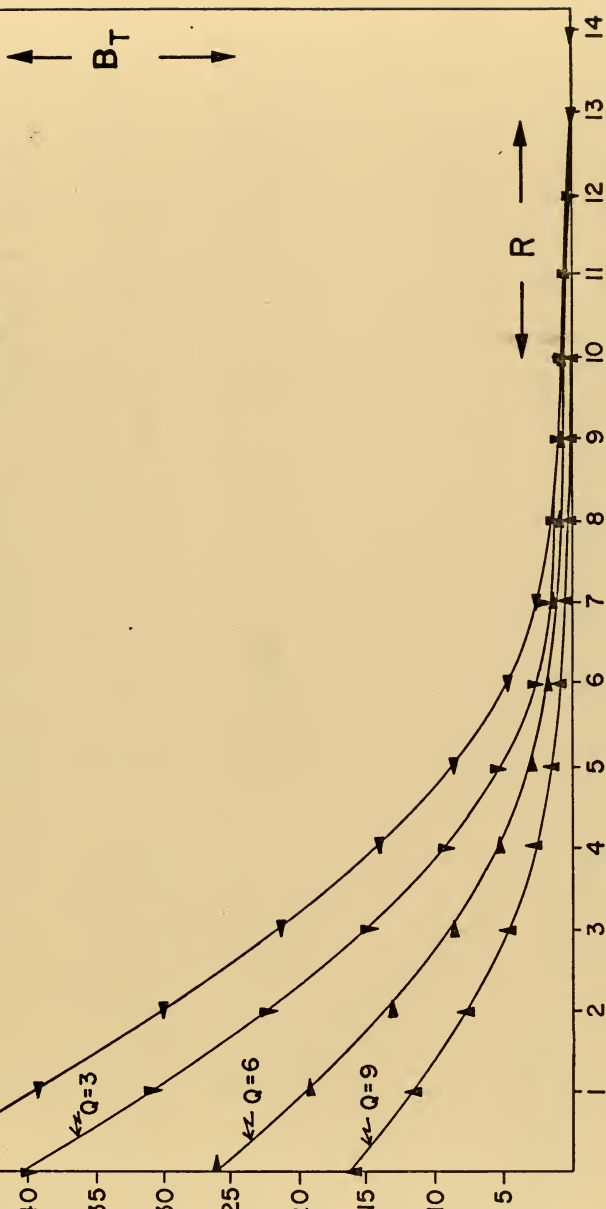
FIGURE 6

TYPICAL RESULTS OF EXPERIMENT FOUR
REORDER POINT (R) VS. UNIT YRS. OF BACKORDERS (B_T) PER UNIT PERIOD
WHERE: $\bar{X} = 1.4$ $Q = 2$
MINIMUM REPAIR BATCH SIZE (L) IS:

L = 4 ▼
L = 3 ▶
L = 2 ▲
L = 1 ◀

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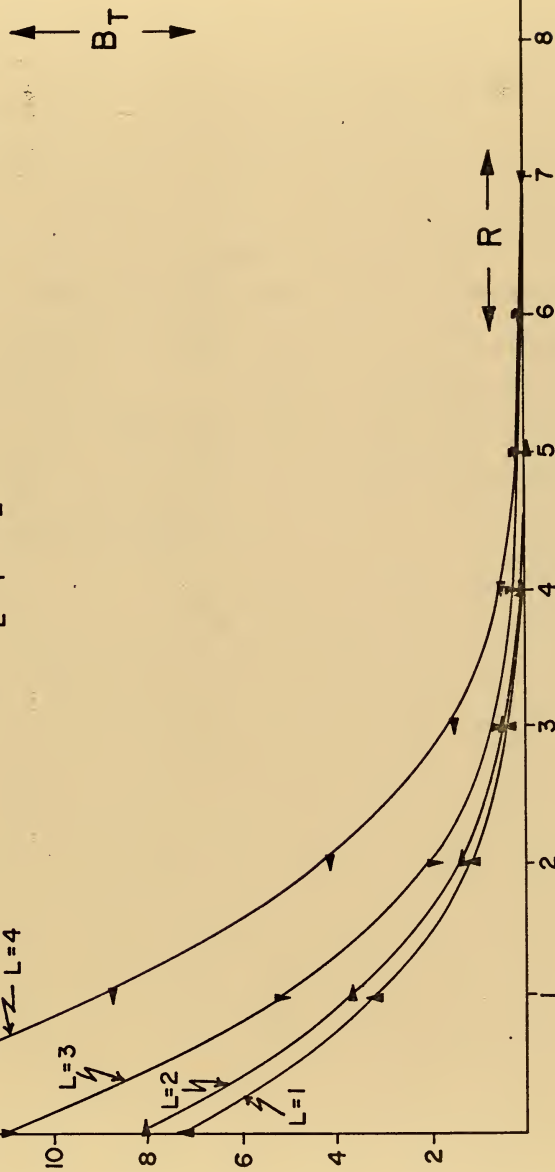
while keeping the mean time between failures constant at
242 hours. The sensitivity of the reorder point was then
investigated by again varying R for each value of $\overline{X}$ until
the expected number of unit years of backorders per unit
period reached a stationary level. A physical interpretation
here could be a change of equipment (perhaps manual repair to
automation) or a change in the budget for the repair depart-
ment. An investigation of the results of this experiment
suggested a comparison of the trade off between decreasing
the mean repair time $(\overline{X}_R)$ and increasing the maximum batch
size in the repair department. The results of experiment
five are presented in Figure 7.

FIGURE 7

TYPICAL RESULTS OF EXPERIMENT FIVE
REORDER POINT (R) VS. UNIT YRS. OF BACKORDERS (B_T)
PER UNIT PERIOD

WHERE: $X = 1.4$
$Q = 2$

MEAN TIME TO REPAIR ONE BATCH OF ITEMS:

$K = 1$ { 336 HRS ●
276 HRS ⊙
216 HRS ▲
195 HRS ◄

$K = 1$ { 180 HRS ▼
156 HRS ▼
096 HRS ■

$K = 4$, 336 HRS X
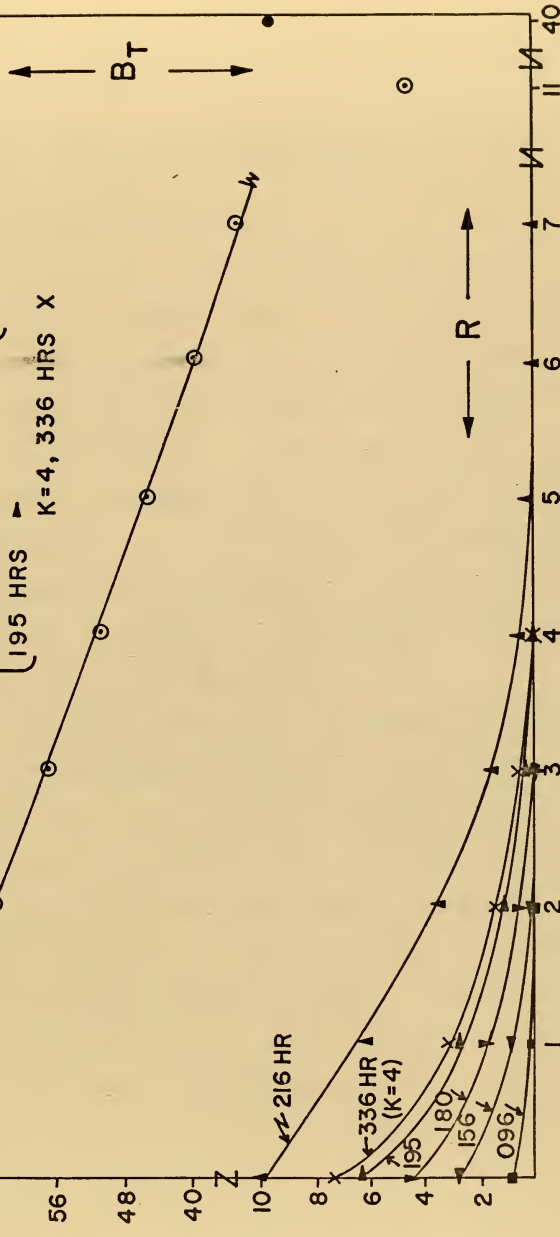
IV. ANALYSIS AND CONCLUSIONS

A. ANALYSIS OF THE FIRST EXPERIMENT

In all experiments the reorder quantity and reorder level were controlled. In addition, for each experiment one variable such as the maximum or minimum repair batch size was controlled while the remaining variables were determined from the simulation. In this experiment, for each reorder quantity and mean demand during repair time considered, the reorder level which reduced the expected number of unit years of backorders per unit period to an acceptable level was determined. To determine this reorder point a one-way analysis of variance was used.

Such a test requires additivity, linearity, normality, independence, and homogeneous variances. The first two assumptions were felt to be satisfied since the expected number of unit years of backorders per unit period appears to be a linear sum of the true mean effect, the true effect of the treatment (the value of the reorder point chosen), and the true effect of the errors observed. The primary error in the observations is due to the stream of random numbers. It seems to be a good assumption that these errors are normally distributed with mean zero and variances which are equal for each treatment.

This particular test was used because it is quite robust, that is, the test is reliable under rather strong modifications

to the above assumptions. It can also be shown that trans-
formations of the original data are justified. This was
particularly important in this case because it was necessary
to make a logarithmic transformation to the observations
in order to obtain a linear model. Figure 8 illustrates
this type of transformation.

The null hypothesis used in this analysis of variance
was that the expected number of unit years of backorders
per unit period for each of the reorder points was the same
for a fixed reorder quantity and mean demand during repair
time. For the parameters considered in this paper the
analysis of variance was reported for that case which
appeared to have the highest probability of not rejecting
the null hypothesis. Nine observations with different
streams of random numbers for each run were made and the
null hypothesis was tested at the .01 significance level.
The results of the analysis of variance yielded a test
statistic of 194, well in excess of the F-value (2.48)
required to reject the null hypothesis. (For calculations
see page 79.)

Since the primary goal of the first experiment was to
determine the "best" order quantity, reorder point combina-
tion, Scheffe's [Ref. 5] multiple comparison test was then
used to find this combination. This procedure tests for
equality of means between contrasts in a systematic fashion
until a significant difference between means is found. The
analysis of variance indicated that a significant difference

FIGURE 8

DATA FROM EXPERIMENT ONE
ORIGINAL B_T CURVE
TRANSFORMED B_T CURVE

$Q = 10$ $\bar{X} = 5.5$

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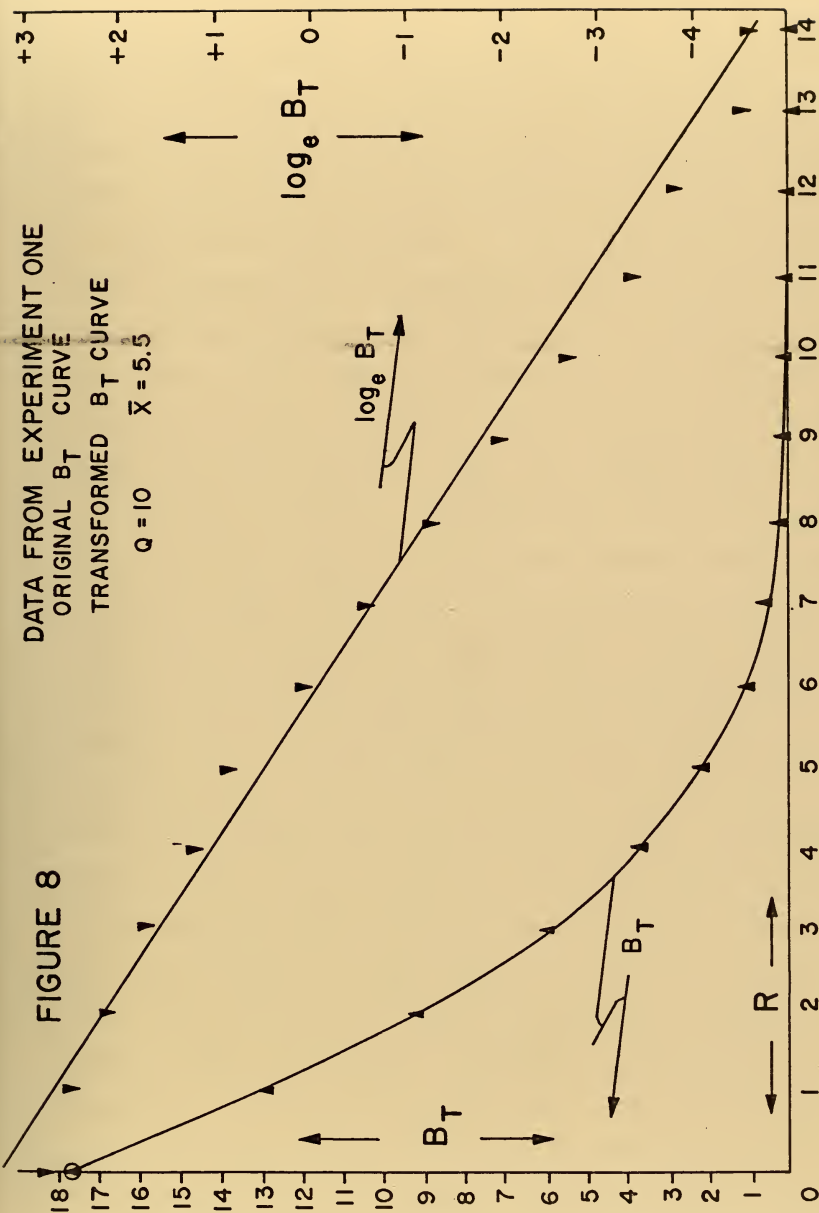
was present. Scheffe's test was then used to determine
the minimum value of the difference in means which statistic-
ally differentiated among the various values of the expected
number of unit years of backorder per unit period.

In order to apply Scheffe's test a (Q,R) pair yielding a
value of the measure of performance which was considered
acceptable was chosen. The first contrast looked at the
differences in the measure of performance for this pair
(Q,R_M) and the pair (Q,R_M-1). If this contrast failed to
reject the null hypothesis, that the expected number of
unit years of backorders per unit period were equal at the
.01 significance level, then the next contrast would examine
the pairs (Q,R_M) and (Q,R_M-2). This procedure continued
until the null hypothesis was rejected. If this happened
when the pairs (Q,R_M) and (Q,R_M-j) were compared, the
minimum value of the differences which was statistically
significant was known to be less than or equal to the
difference between the values of the measure of performance
for these two pairs. For future reference denote R_M-j by R_Q.
The minimum difference required for significance can be
solved for exactly by applying this procedure in reverse,
that is, by setting the value of an arbitrary contrast
equal to the test statistic required to reject the null
hypothesis and then transforming this contrast into the
difference required in the measure of performance for
significance. For the example systems considered in this
paper this procedure required the use of three contrasts

before significance was found between (Q,R) pairs (10,11) and (10,8). This contrast resulted in a test statistic of 6.99 which was greater than the F-value (2.48). Hence, the null hypothesis was rejected. (For calculations see pages 81-83). Further, forcing the test statistic to be equal to 2.48 and solving for the required minimum difference between values of the measure of performance for significance resulted in a value of 0.096 unit years of backorders per unit period. Statistically, one cannot distinguish a difference between 0.096 and 0.00 for this measure of performance. For this particular example, which is summarized in Tables IV and V, this means that any position to the right of the dashed line in Table IV could be an acceptable operating point for a system when X, the mean demand during repair time, was 5.5 and the other system characteristics were as noted in Tables II and III.

The procedure then used to determine the "best" operating point for this particular example was to list the pairs (Q,R_Q) and observe the measures of performance listed in Table I. Notice from Table V that when one tries to identify the pair that minimizes both the average number of items on hand at an arbitrary point in time and the average number of procurements per unit period the (Q,R_Q) pairs (2,10) and (3,10) are selected as the "best" operating points for this example. A simple comparison of holding cost and procurement cost could enable the user to further distinguish between these two choices.

TABLE IV. TYPICAL RESULTS FROM EXPERIMENT ONE WITH B_T SIGNIFICANCE LINE DRAWN IN. SUMMARY TABLE OF THE EXPECTED NUMBER OF UNIT YEARS OF BACKORDERS PER UNIT PERIOD FOR VARIOUS (Q,R) PAIRS

$\overline{X}$=5.5 (mean demand during repair time)

| Order Quantity Q | R_1 Reorder Points | | | | | | | | | | | | |
	0	1	2	3	4	5	6	7	8	9	10	11	12
1	49.20	39.42	30.08	21.35	14.19	8.62	4.71	2.30	0.97	0.34	0.10	0.05	0.02
2	43.38	33.86	24.95	17.22	10.93	6.45	3.38	1.52	0.56	0.20	0.09	0.05	0.02
3	39.88	30.63	22.09	14.84	9.09	5.00	2.39	1.02	0.40	0.16	0.08	0.05	0.02
4	35.18	26.13	18.56	12.42	7.64	4.23	2.12	0.96	0.40	0.18	0.09	0.05	0.02
5	29.90	21.99	15.40	10.13	6.22	3.44	1.78	0.80	0.30	0.13	0.06	0.03	0.02
6	26.08	19.02	13.07	8.50	5.21	2.92	1.48	0.69	0.30	0.14	0.08	0.05	0.02
7	24.54	17.73	12.17	7.78	4.56	2.45	1.29	0.64	0.25	0.08	0.03	0.00	0.00
8	20.33	14.30	9.60	6.07	3.57	1.94	0.94	0.43	0.18	0.09	0.03	0.01	0.00
9	16.04	11.17	7.50	4.70	2.78	1.33	0.59	0.22	0.08	0.02	0.00	0.00	0.00
10	17.61	12.93	9.07	6.07	3.74	2.17	1.17	0.60	0.20	0.13	0.04	0.01	0.00

TABLE V. SUPPLY PERFORMANCE MEASURES FOR EXPERIMENT ONE

SUMMARY STATISTICS FOR, RIGHT ADJACENT, (Q,R) PAIRS ADJACENT TO B_T SIGNIFICANCE LINE

$\overline{X}=5.5$ (MEAN DEMAND DURING REPAIR TIME)

Order Quantity Q	FILLS	X% FILRT	B	B_T	BARB	X% RDYRT	OH	ORD	RI	C	DIFF 1	DIFF 2	R_Q
10	1471	99.50	6	0.06	0.00	100	9.52	15	1337	5.08	-0.20	.006	10
9	1464	99.12	13	0.08	0.01	99.38	7.61	16	1337	5.08	0.39	.007	8
8	1464	99.12	13	0.09	0.00	100	7.89	18	1337	5.08	0.37	.009	9
7	1457	98.65	20	0.08	0.00	99.38	7.12	21	1337	5.08	-0.10	.008	9
6	1465	99.19	12	0.08	0.00	100	7.73	24	1337	5.08	0.34	.008	10
5	1470	99.43	7	0.06	0.00	100	7.20	29	1337	5.08	-0.01	.006	10
4	1462	98.99	15	0.09	0.00	100	6.77	36	1337	5.08	0.04	.009	10
3	1465	99.19	12	0.08	0.00	100	6.14	47	1337	5.08	-0.08	.008	10
2	1462	98.99	15	0.09	0.00	100	5.76	71	1337	5.08	0.04	.009	10
1	1470	99.43	7	0.05	0.00	100	6.17	141	1337	5.08	-0.05	.005	11

In applying these results to other systems it was observed that the value of 0.096 for the expected number of unit years of backorders per unit period could also be used to determine the (Q,R_Q) candidates for the "best" operating point when considering all values of mean demand during repair time less than or equal to 5.5. It was further observed that among these (Q,R_Q) candidates, most measures of performance would differ by negligible amounts with the exception of the average number of items on hand at an arbitrary point in time and the average number of procurements made per unit period.

B. ANALYSIS OF EXPERIMENTS TWO THROUGH FIVE

1. General Comments

The analysis of variance and the multiple comparison test could have been used to obtain candidates for optimal operating points with other relevant parameters, such as the minimum or maximum repair batch sizes or the distribution of repair time being used as the basis. Although this analysis was not repeated for all experiments, a close observation of the data seemed to indicate that the minimum significant difference value would be nearly the same regardless which parameter was chosen for the basis. Use of this observation was made in the analysis of experiments two through five.

2. Repair Time Distribution (Second Experiment)

The results summarized in Tables VI and VII showed that the type of repair time distribution had a negligible

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TABLE VI. TYPICAL RESULTS FROM EXPERIMENT TWO WITH B_T SIGNIFICANCE LINE DRAWN IN.

SUMMARY TABLE OF THE EXPECTED NUMBER OF UNIT YEARS OF BACKORDERS PER UNIT PERIOD

FOR VARIOUS (DIST'N TYPE, R) PAIRS

$\overline{X}=5.5$ (MEAN DEMAND DURING REPAIR TIME) Q=10 (REORDER QUANTITY)

| DISTRIBUTION TYPE | R, (REORDER POINTS) | | | | | | | | | | | | |
	0	1	2	3	4	5	6	7	8	9	10	11	12
CONSTANT	15.29	10.91	7.49	4.76	2.75	1.46	0.75	0.41	0.22	0.11	0.06	0.03	0.00
UNIFORM	15.39	10.62	7.07	4.40	2.55	1.32	0.69	0.37	0.21	0.12	0.06	0.03	0.01
NORMAL	15.10	10.95	7.42	4.73	2.87	1.66	0.89	0.46	0.25	0.13	0.05	0.01	0.00
EMPIRICAL	15.69	10.84	7.46	4.81	2.82	1.45	0.65	0.26	0.10	0.03	0.01	0.00	0.00

TABLE VII. SUPPLY PERFORMANCE MEASURES FOR EXPERIMENT TWO

SUMMARY STATISTICS FOR, RIGHT ADJACENT, (DIST'N TYPE, R) PAIRS ADJACENT TO B_T SIGNIFICANCE LINE

DISTRIBUTION TYPE	FILLS	%FILRT	B	B_T	BARB	%RDYRT	OH	ORD	RI	C	DIFF 1	DIFF 2	R
CONSTANT	1421	99.29	10	.06	.005	99.40	9.61	14	1292	5.05	-0.10	.001	10
UNIFORM	1418	99.08	13	.06	.005	98.81	9.63	14	1292	5.02	-0.08	.001	10
NORMAL	1417	99.01	14	.05	.011	98.27	9.58	14	1292	5.08	-0.13	-.006	10
EMPIRICAL	1423	99.35	8	.03	.000	100	8.69	14	1292	4.96	-0.02	.073	9

effect on the expected number of unit years of backorders per
unit period provided the mean repair times were the same.
This result was expected since Palm's theorem indicates that
the distribution of the number of items in repair depends
only on the repair time distribution through its mean value.
When the probability of repair was nearly one it was also
observed that the type of lead time distribution had a
negligible effect on system performance. A probable
explanation for this result is that the average number of
orders placed per unit period was insignificant compared to
the number of repairs made. This can be seen in Table VII.

3. Maximum Batch Size Test (Third Experiment)

In this experiment the effects of change in the
maximum repair batch size were investigated. The results
summarized in Tables VIII and IX indicate a vast improvement
in system performance for increasing the maximum batch size
from one to two but negligible improvement thereafter. The
initial improvement can be explained by the queueing result
which says that in order to ensure stationarity the maximum
repair batch size must be large enough to guarantee that the
mean time between failures multiplied by K must be greater
than the mean repair time. An important question which was
considered was exactly how large K should be. In order to
provide an answer further work would have to be done to
determine an explicit rule for finding the "best" value of K.
However, it is felt that this rule would depend on the
utilization factor of the repair department. For this

TABLE VIII. TYPICAL RESULTS FROM EXPERIMENT THREE WITH B_T SIGNIFICANCE LINE DRAWN IN. SUMMARY TABLE OF THE EXPECTED NUMBER OF UNIT YEARS OF BACKORDERS PER UNIT PERIOD FOR VARIOUS (K,R) PAIRS

$\overline{X}=1.4$ (MEAN DEMAND DURING REPAIR TIME)   Q=2   L=1

MAX BATCH SIZE (K)	R, REORDER POINTS									
	0	1	2	3	4	5	6	7	...	40
1	227.20	193.90	185.90	177.70	170.00	162.40	154.80	146.50	...	31.70
2	9.68	4.35	1.78	0.57	0.23	0.07	0.01	0.00		
3	7.49	3.31	1.24	0.41	0.16	0.03	0.01	0.00		
4	7.26	3.18	1.19	0.37	0.13	0.03	0.01	0.00		
5	7.20	3.13	1.15	0.33	0.13	0.03	0.01	0.00		
6	7.20	3.13	1.15	0.33	0.13	0.03	0.01	0.00		

TABLE IX. SUPPLY PERFORMANCE MEASURES FOR EXPERIMENT THREE

SUMMARY STATISTICS FOR, RIGHT ADJACENT, (K,R) PAIRS ADJACENT TO B_T SIGNIFICANCE LINE

	FILLS	FILRT	B	B_T	BARB	RDYRT	OH	ORD	RI	C	DIFF 1	DIFF 2	R
2	339	99.12	3	.07	.006	96.95	4.24	17	218	2.01	-0.80	.001	5
3	339	99.12	3	.03	0	96.95	4.39	17	213	1.86	-0.65	.003	5
4	339	99.12	3	.03	0	97.65	4.44	17	213	1.81	-0.60	.003	5
5	339	99.12	3	.03	0	97.65	4.45	17	212	1.80	-0.59	.003	5
6	339	99.12	3	.03	0	97.65	4.45	17	212	1.46	-0.59	.003	5

particular example, increasing K to obtain a utilization factor of less than .417 resulted in negligible improvement in system performance.

4. Minimum Batch Size Test (Fourth Experiment)

This experiment considered the effects of change in the minimum batch size for a fixed value of K. The results summarized in Tables X and XI indicated that, as before, changes in the minimum batch size requirement had little effect in overall system performance with the exception of the average number of repair inductions. If the cost of a repair induction is large certain economies could be achieved by requiring a minimum batch size. This could be achieved without degrading system performance. Further investigation would be needed to generalize these results in order to obtain a rule for determining the "best" value for the minimum batch size.

5. Mean Repair Time Test (Fifth Experiment)

For the case in which both K and L are one, the effects of change in the mean repair time were examined. The results summarized in Tables XII and XIII indicated that, as expected, the magnitude of the mean repair time is highly significant. In particular, system effectiveness was inversely proportional to the mean repair time.

TABLE X. TYPICAL RESULTS FROM EXPERIMENT FOUR WITH B_T SIGNIFICANCE LINE DRAWN IN.

SUMMARY TABLE OF THE EXPECTED NUMBER OF UNIT YEARS OF BACKORDERS PER UNIT PERIOD

FOR VARIOUS (L,R) PAIRS

$\overline{X}=1.4$ (MEAN DEMAND DURING REPAIR TIME)   Q=2   K=4

MIN BATCH SIZE (L)	R, REORDER POINTS								
	0	1	2	3	4	5	6	7	8
4	15.65	8.88	4.17	1.57	0.50	0.13	0.02	0.01	0
3	11.06	5.23	1.97	0.69	0.23	0.08	0.02	0	0
2	7.97	3.59	1.24	0.40	0.13	0.02	0	0	0
1	7.26	3.18	1.19	0.37	0.13	0.03	0.01	0	0

TABLE XI. SUPPLY PERFORMANCE MEASURES FOR EXPERIMENT FOUR

SUMMARY STATISTICS FOR, RIGHT ADJACENT, (L,R) PAIRS ADJACENT TO B_T SIGNIFICANCE LINE

MIN BATCH SIZE	FILLS	FILRT	B	B_T	BARB	RDYRT	OH	ORD	RI	C	DIFF 1	DIFF 2	R
4	339	99.12	3	0.02	0	97.56	4.60	17	77	2.67	-0.73	.003	6
3	337	98.67	5	0.08	0	97.56	3.84	17	101	2.41	-1.20	.008	5
2	340	99.41	2	0.02	0	98.17	4.26	17	142	1.99	-0.78	.002	5
1	339	99.12	3	0.03	0	97.56	4.44	17	213	1.81	-0.60	.003	5

TABLE XII. TYPICAL RESULTS FROM EXPERIMENT FIVE WITH B_T SIGNIFICANCE LINE DRAWN IN.

SUMMARY TABLE OF THE EXPECTED NUMBER OF UNIT YEARS OF BACKORDERS PER UNIT PERIOD

FOR VARIOUS (TIME, R) PAIRS

$\overline{X}=1.4$, MEAN TIME BETWEEN DEMANDS=242 HOURS, Q=2, K=1, L=1

R, REORDER POINTS

MEAN TIME TO REPAIR IN HOURS	0	1	2	3	4	5	6	7	...	11....21...40
336	227.20	193.90	185.90	177.70	170.00	162.40	154.90	146.50	...	131.30 ... 31.70
276	79.20	70.70	63.30	57.10	51.30	45.70	40.30	35.00	...	15.40 0.59
216	10.16	6.16	3.41	1.62	0.56	0.16	0.01	0		
195	6.20	2.97	1.08	0.23	0.04	0	0	0		
180	4.68	1.90	0.44	0.03	0	0	0	0		
156	2.83	0.84	0.08	0	0	0	0	0		
096	0.81	0.11	0	0	0	0	0	0		
*336 (K=4)	7.26	3.18	1.19	0.37	0.13	0.03	0.01	0	0	0

*This entry is included here so one can compare decreasing mean time versus increased K.

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TABLE XIII. SUPPLY PERFORMANCE MEASURES FOR EXPERIMENT FIVE

SUMMARY STATISTICS FOR,RIGHT ADJACENT, (TIME, R) PAIRS ADJACENT TO B_T SIGNIFICANCE LINE

Q=2   K=1

MEAN REPAIR TIME (HOURS)	FILLS	FILRT	B	B_T	BARB	RDYRT	OH	ORD	RI	C	DIFF 1	DIFF 2	R
336 (K=1)	329	96.19	13	31.70	3.33	96.95	19.26	17	260	24.80	--	--	40
276	327	95.62	15	0.59	0.06	92.89	10.86	17	312	11.44	--	--	21
216	340	99.41	2	0.01	0	99.40	5.59	17	315	1.80	-0.89	.001	6
195	336	98.25	6	0.04	0	98.81	4.02	17	315	1.37	-0.54	.004	4
180	335	97.96	7	0.03	0	98.22	3.27	17	315	1.19	-0.35	.003	3
156	326	95.92	14	0.08	0	93.49	2.54	17	316	0.85	-0.17	.008	2
096	342	100.00	0	0	0	99.40	2.94	17	318	0.46	0	0	2
*336 (K=4)	339	99.12	3	0.03	0	97.65	4.44	17	213	1.81	-0.60	.003	5

*This entry is included here so one can compare decreasing mean time versus increased K.

C.   CONCLUDING COMMENTS ABOUT THE ANALYSIS

It is interesting to note the tradeoffs between various parameters. For instance, it seemed that one could determine a reduction in mean repair time which would give an equivalent increase in system performance to that provided by an increase in the maximum repair batch size. An illustration of such a tradeoff for the example considered in this paper can be seen by looking at Table XIII for the following entries: minimum and maximum batch size of one with mean repair time of 216 versus minimum batch size of one, maximum batch size of four, and mean repair time of 336 hours.

Decisions such as determining the maximum batch size or mean repair time must be made by the decision maker based on the feasibility of change and the cost of such a change. This simulation will provide the manager with each of the measures of performance needed to make such decisions.

In addition to the above remarks, another item should be discussed. Recall that one of the objectives of this study was to demonstrate the analytical results obtained by Richards [Ref. 7]. Notice that in each of the tables which summarized the measures of performance for the various experiments, two of the measures of performance listed are "DIFF 1" and "DIFF 2." "DIFF 1" reflects the difference between the simulated and theoretical values for the average number of items on hand at an arbitrary point in time. "DIFF 2" reflects the difference between the expected number

of unit years of backorders per unit period and the average
number of items on backorder at an arbitrary point in time.
In observing these differences in Table V it was noted that
the maximum value for "DIFF 1" was 0.39 and for "DIFF 2"
it was .009. This represents a maximum percentage differ-
ence of 5.1% for "DIFF 1." It is felt that since these
differences are so small, this simulation does in fact
demonstrate the validity of the analytical results obtained
by Richards.

V.   PROGRAM GUIDE

This section is written so that, along with Table I
(Supply Performance Measures) and the table of symbols and
abbreviations, it can be a self contained unit for the user.
It contains all the information needed to successfully set
up and run the model.

A.   GENERAL COMMENTS

Most people will agree that any inventory system should
be designed to give the maximum amount of service for the
minimum amount of cost possible. Hence most inventory
studies evaluate the various policies being considered by
looking at the costs incurred over a unit period of time.
Then policy A is chosen over policy B if the total expected
cost per unit time using policy A is less than when using
policy B. However, quite often in this approach one cannot
specify all the cost elements. An alternative approach is

to determine the average values of such measures of perform-
ance as the number of items on hand at an arbitrary point
in time, the number of backorders per unit period, and others
as listed in Table I. The user can then choose from these
measures of performance those he wishes to use to evaluate
the policies under his scrutiny. This method provides the
user with an easy way of deciding which values for system
parameters such as the reorder quantity and reorder point
yield satisfactory performance.

Closed form solutions can be obtained for the various
measures of performance but often the solutions are not very
tractable for further calculations. This is where the
simulation is of value. It systematically and quickly
calculates the magnitude of all the measures of performance
for various input values of all parameters involved and
presents the user with a fast and easy means of investigating
the sensitivity of his inventory system to any changes in
these parameters. To try and do this procedure by hand or
apply the analytical results to a sensitivity analysis of
this size would involve a large number of man-hours of work
to produce effective results.

B. EVENTS

This model is an event-step computer simulation written
in the GPSS/360 language, i.e., all actions that are to
occur in the simulation are dynamically generated by the
computer program as a result of previous simulation actions

and are listed chronologically in order of descending

priority in a Current Events Chain, Future Events Chain,

or Interrupt Chain. For purposes of programming, each of

the major actions included in the simulation can be con-

sidered as an entity in itself and assumes the form of a

computer program subroutine. Such major actions have been

called events for convenience. The eight major actions

(events) included in the simulation are:

(1) Item Failure
(2) Item Inspection
(3) Scrap
(4) Repair
(5) Issue
(6) Backorder
(7) Order
(8) Receipt of Material

Each of the computer program subroutines representing

these events uses as input parameters the following informa-

tion:

(1) Time the event is to occur
(2) Identification of event
(3) Number of items involved
(4) Priority level (0,1,...)
(5) Current values of system characteristics such as
     inventory position (IP), number of items ready for
     issue (D), and others.

The dynamic process of simulating one inventory policy

from start to finish forms the executive routine for the

computer simulation. This executive routine also includes

three program subroutines referred to as Random Observation,

Calculation of Measures of Performance, and Incrementation

of System Parameters. General flow charts describing the

logic included in each event of the simulation plus the

interrelationship of events are included as Figures 9 through
12. Detailed flow charts for the entire model are provided
in Appendix B. Random observation is the subroutine that
generates random points in time at which certain parameter
values are recorded in order to obtain certain useful sta-
tistics about the system. Calculation of Measures of
Performance is the subroutine that, at the completion of
any unit period (a time period which represents 10 years
of actual system operations), interrogates the information
contained in all system parameters and transfers control of
the computer program to the calculation phase of the measures
of performance listed in Table I. Incrementation of system
parameters is the subroutine which increments the current
value of R, the reorder point, by one. It also clears the
results of the last unit period from the program and resets
all the random number generators to the same values used in
the previous run to ensure meaningful comparisons between
runs.

C. INPUT

All inputs to the computer program are contained on
three punched cards called Initial Cards and four Function
Follower Cards. The format for this information and the
units to be used are detailed in Tables XIV through XVI.
With one set of input cards a user can simulate the inter-
actions involved for as long as 140 years or 14 unit periods
of ten years each. Each unit period will increment the
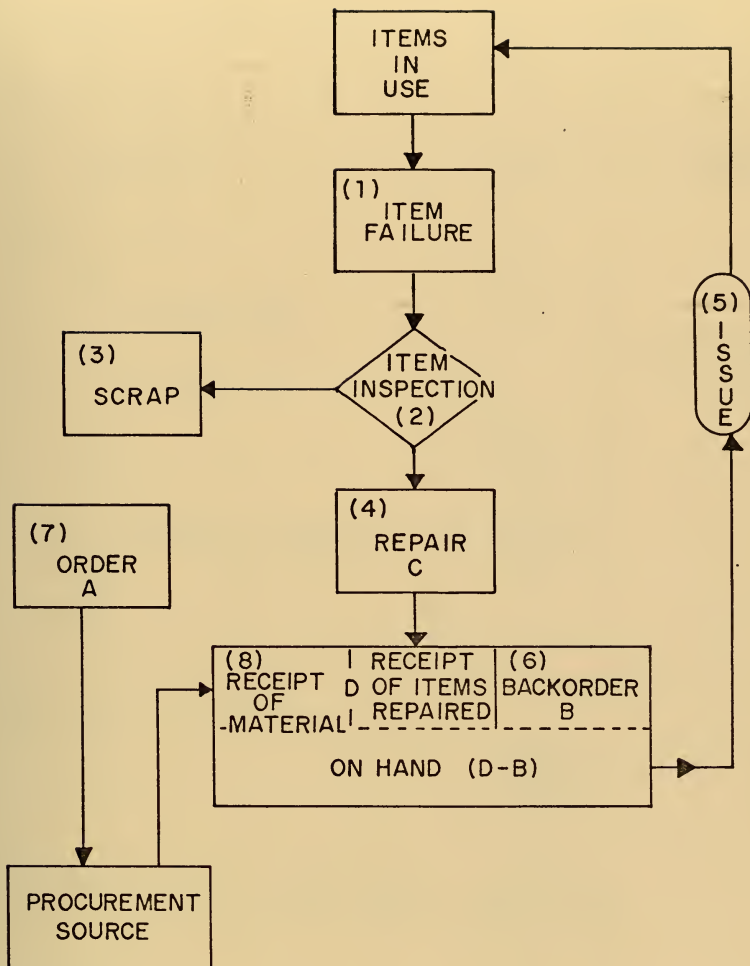
Figure 9. Relationships of events.

Figure 10. Major Events (1)-(4) Logic Diagrams.
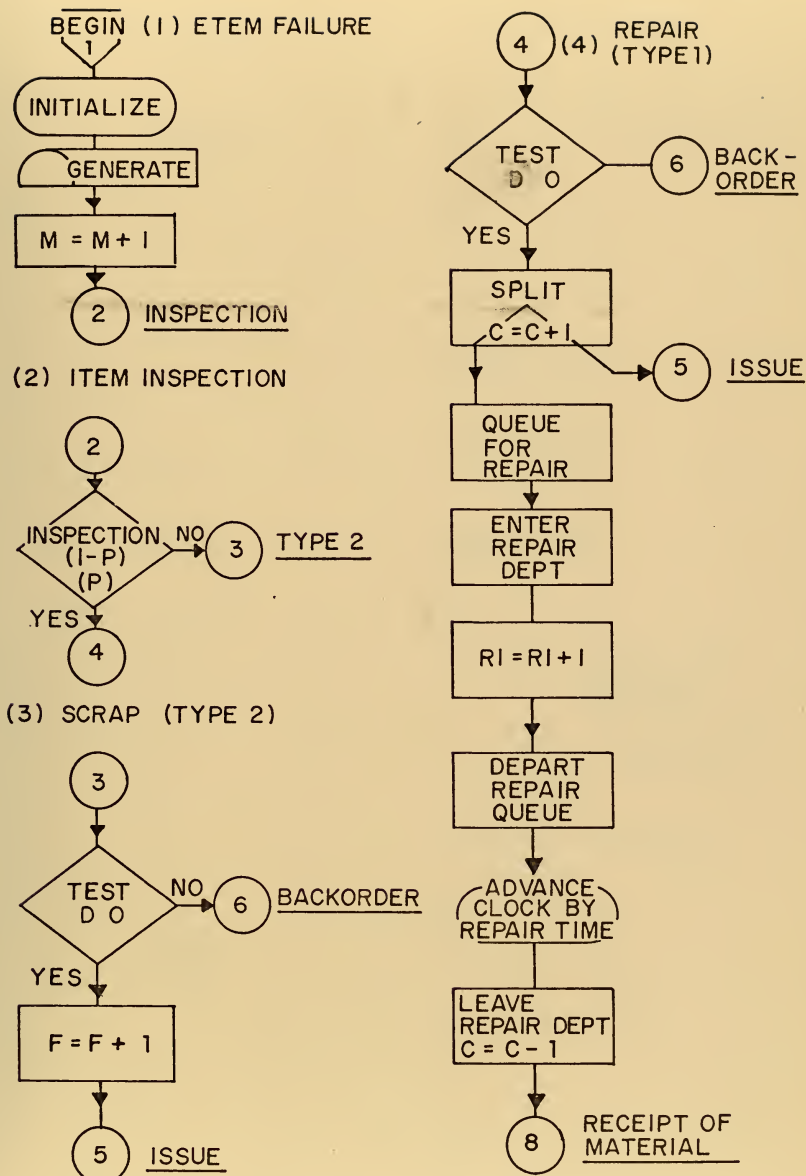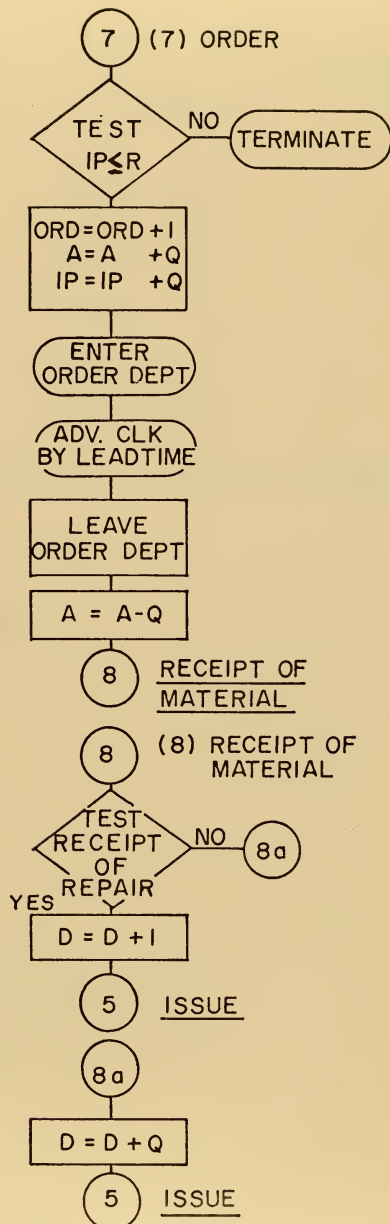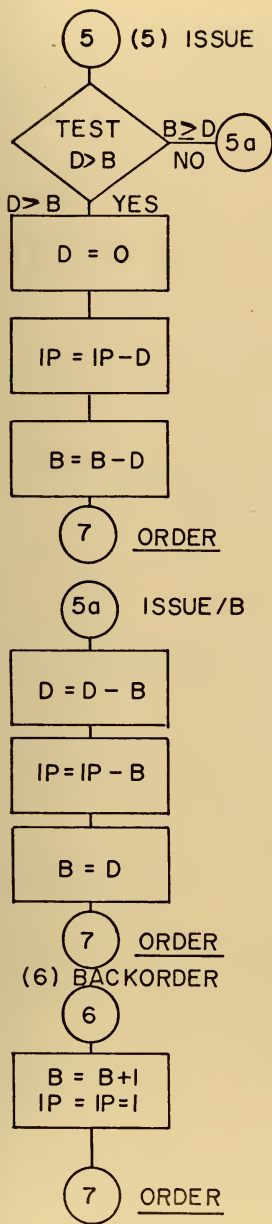
Figure II. Major Events (5)--(8) Logic Diagrams.

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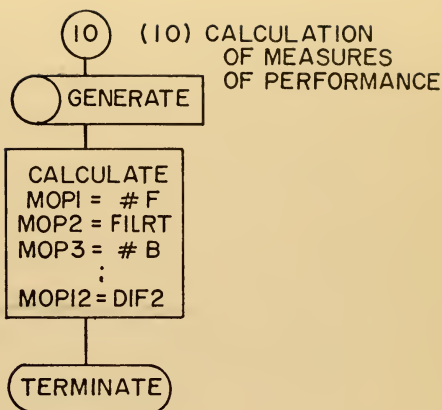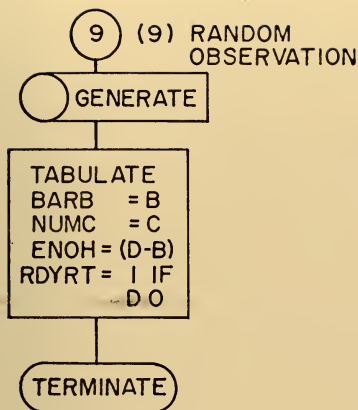
(11) Incrementation of system parameters and control of program running time.

CLEAR
RMULTXXXX
START
.
CLEAR
RMULTXXXX
START
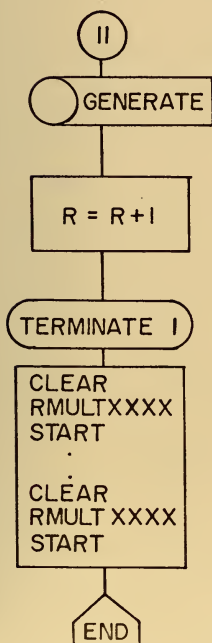
This clears all values from program. It also resets the random number generator so the same number of XA's are created for each successive unit period.

Figure 12.

Administrative events (9) – (11) logic diagrams.

value of R by one starting with the initial value chosen by
the user (generally zero). In order for the user to vary
parameter values other than the reorder level, a new set of
initial cards must be prepared by the user for the program.
All input values must be integers and in units of hours if
it is a time input. For example in the three columns allotted
for Q on card one the user could enter anything from 001 to
999 for one item up to 999 items or in the columns allotted
for μ_D, the mean time between demands (failures), on card
two the user could enter anything from 999 to 001 to repre-
sent failures rates of .7308 per month (one every 999 hours)
to 730 per month (one every hour).

D. FORMAT SECTION

    This section contains the tables which identify and
explain the various system parameters and characteristics
needed as user input in order to use the simulation. It
also includes the feasible range for each entity. This
input must be typed by the user on three Initial Cards and
four Function Follower Cards.

    1. Description Of Entities Found On The Initial Cards
        This input is summarized in Tables XIV through XVI.
    2. Description Of Function Follower Cards One and Two
        These cards contain the function values, Y_i, and
argument values, X_j, for the empirical distribution of
repair time. This is a discrete numerical valued function
with up to ten different points. Figure 12 shows that this

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TABLE XIV.   FIRST INITIAL CARD

Q   Reorder quantity. Number of items reordered at
           one time.

R   Reorder Point. If Inventory Position is $\leq$ R an
           order is placed.

L   Minimum Batch Size. Under the batch repair policy,
           repair won't start unless at least L units are
           currently waiting to be repaired. Ensure L=0 if
           the infinite server queueing policy for repair is
           desired.

K   Maximum Batch Size. Under the batch repair policy,
           this is the maximum number of items that can be
           repaired at one time.

P   Probability of Repair. The probability that a
           failed item can be repaired. If P=0000, (P=0.0)
           the model degenerates to the consumables case.
           If P=1000, (P=1.0) the model becomes one without
           degredation of supply which implies that no orders
           are placed and no outside procurement is needed.

μ_D Mean time between failures. The expected number of
           hours between demand.

FLAG/R   Repair Time Distribution Flag. One of four numbers.
           3   Constant repair time.
           4   Uniform distribution for repair time.
           5   Normal distribution for repair time.
           6   Empirical distribution for repair time.

TABLE XV. SECOND INITIAL CARD

μ_R Mean Time For Repair. The expected time required for repair of an item or batch of items.

LBR   Minimum Repair Time. The lower bound on repair time for the uniform distribution of repair time (used when FLAG/R=4).

UBR   Maximum Repair Time. The upper bound on repair time for the uniform distribution of repair time, (used when FLAG/R=4).

σ_R Standard Deviation For Repair Time. The standard deviation for the normal distribution of repair time, (used when FLAG/R=5).

FLAG/R   Lead Time Distribution Flag. One of four numbers.
      7   Constant lead time.
      8   Uniform Distribution for lead time.
      9   Normal Distribution for lead time.
      10   Empirical Distribution for lead time.

μ_L Mean Time For Procurement. The expected value for procurement lead time.

TABLE XVI. THIRD INITIAL CARD

LBL   Minimum Lead Time. The lower bound on lead time for the uniform distribution of lead time.

UBL   Maximum Lead Time. The upper bound on lead time for the uniform distribution of lead time.

σ_L Standard Deviation For Lead Time. The standard deviation for the normal distribution of lead time.

XH17   Type Of Output Desired Flag. One of two numbers. Zero for summary output, or one for standard output. (Normally a zero should be used to conserve printing time.)

function has the same function value, $FN_j = Y_i$, for all argument values in the interval between $X_j - 1$ and X_j. No interpolation is performed, and the vlaue at the right-hand end of the interval is used. For argument values less than the magnitude of X_1, $FN_1 = Y_1$. For argument values greater than the last value of X_j, $FN_n = Y_n$.

The function follower cards contain the individual points (successive pairs of X_j, Y_j values) of the function. For example, consider the function pictured in Figure 12 as the repair time distribution, the function follower cards would then be: 0.06,439/0.07,439/0.08,439/0.58,464/0.66,486/ 0.68,558/0.69,558/0.71,558/0.96,582/1.0,606.

Notice that in this example there are really only six different function values FN_j, so argument values .06, .07, .68, and .69 are dummy values and are put in only to meet the requirement of having ten pairs of X_j,Y_j values.

3. <u>Description Of Function Follower Cards Three and Four</u>

These cards are used exactly the same way as Function Follower Cards One and Two except they contain the function and argument values for the empirical distribution of lead time. For example, if the function pictured in Figure 13 were the lead time distribution, FFC's three and four would be: 0.2,360/0.4,384/0.5,432/0.6,480/0.8,768/0.9,840/ 0.95,864/0.99,888/0.995,912/0.999,984.

Notice that once FLAG/R and FLAG/L have been selected the program ignores those cards which involve the parameters of the other distributions. Therefore only those

Discrete numerical valued function with IO arguments and duplicate function values for sample empirical repair time.

Discrete numerical valued function with IO arguments, no duplicate function values but with argument $X_n < 1.0$.˙. function values for $.T15 < X \le 1.0$ FN = 984. (sample empirical lead time.)
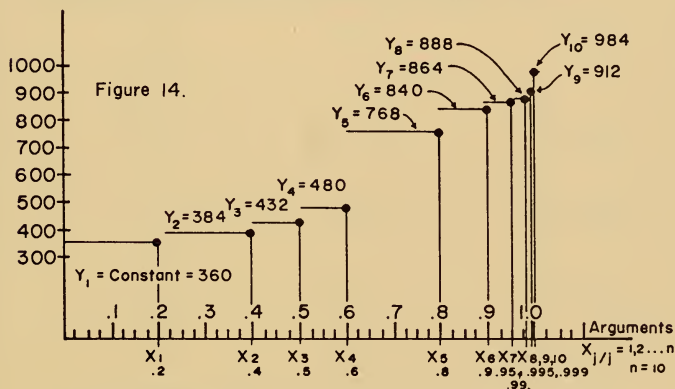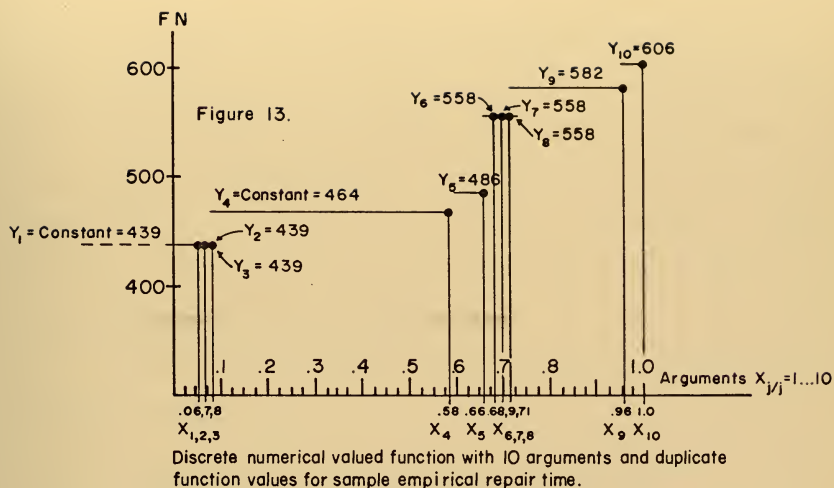
values or cards which affect the parameter values of the
particular type of distribution specified need be worried
about. For example, if FLAG/R=5 and FLAG/L=10, the user
must ensure μ_R, σ_R and μ_L have the values desired and FCC's
three and four have the values desired. The values of LBR,
UBR, LBL, UBL, σ_L, and FFC's one and two can be ignored.

4. Examples of Initial Cards

Tables XVII through XIX give examples of the three
Initial Cards.

TABLE XVII. EXAMPLE OF INITIAL CARD ONE

Columns	Name	Range	Units
8-14	INITIAL		
19-22	XH1;		
23-24	Q	1-99	ITEMS
25-29	/XH2,		
30-31	R	0-99	ITEMS
32-36	/XH3,		
37-38	L	0-K	ITEMS
39-43	/XH4,		
44-45	K	0-99	ITEMS
46-50	/XH5,		
51-54	P	0-1000	.001
55-59	/XH6,		
60-62	μ_D	0-999	HOURS
63-67	/XH7,		
68-69	FLAG/R	3,4,5, or 6	NONE

All input information is right-justified in the
space allotted. Example:

COLUMN NUMBER -   28   39   55   69
                   ↑   ↑   ↑   ↑
INITIAL   XH1,10/XH2,01/XH3,00/XH4,01/XH5,0900/XH6,061/XH7,03

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TABLE XVIII. EXAMPLE OF INITIAL CARD TWO

Columns	Name	Range	Units
8-14	INITIAL		
19-22 23-25	XH8, μ_R	0-999	HOURS
26-30 31-33	/XH9, LBR	0-998	HOURS
34-39 40-43	/XH10, UBR	0-998	HOURS
44-49 50-52	/XH11, σ_R	0-580	HOURS
53-58 59-60	/XH12, FLAG/L	7,8,9, or 10	NONE
61-66 67-69	/XH13, μ_L	0-999	HOURS

  All input information is right-justified in the space allotted. Example:

```
COLUMN NUMBER -         34                    53                      69
                         ↑                     ↑                       ↑
INITIAL   XH8,336/SH9,168/XH10,0504/XH11,095/XH12,07/XH13,504
```

TABLE XIX. EXAMPLE OF INITIAL CARD THREE

Columns	Name	Range	Units
8-14	INITIAL		
19-23 24-26	XH14, LBL	0-998	HOURS
27-32 33-36	/XH15, UBL	0-1998	HOURS
37-42 43-45	/XH16, σ_L	0-580	HOURS
46-51 52	/XH17,	0, or 1	NONE

  All input information is right-justified in the space allotted. Example:

```
COLUMN NUMBER - 26               37                   51
                 ↑                ↑                    ↑
INITIAL   XH14,240/XH15,0768/XH16,116/XH17,0
```

E.   OUTPUT

The computer program has two different sets of output,
summary (special) and standard. The type of output received
depends on the value of XH17. If XH17=0 the summary output
is received, but if XH17=1 the standard output is received.
Computer running and printing time is greatly increased if
the standard output is used. Therefore, it is recommended
that XH17 be set to zero. If there is a major error in the
program, the standard output will be printed out automatic-
ally. Following is an explanation of the two sets of output.

1.   Summary Output

An example of the summary output is illustrated in
Appendix D. Notice that there are three major divisions:
(1) savevalues, (2) storage statistics and (3) queue
statistics.

a.   Savevalues

There are four subdivisions in this part. The
first is a list of nonzero halfword savevalues between
five and 100 for system parameters and statistics. This
list is included for completeness only and not because of
their nature or importance. The second subdivision, Clock
Time, merely shows the number of hours of operation
simulated. Normally this will be 87600 hours or ten years
of operation, which has been defined to be a unit period.
The third subdivision, Critical System Parameters, lists
the values of Q, K, and L which the user has chosen and
input on the initial cards. It also prints out the value

of R for this particular time period. The last subdivision,
Measures of Performance, includes most of the important
statistics to be considered when judging or comparing
alternative inventory systems.

b. Storage Statistics

This division provides the important statistics
for the order department (ORDER), the infinite server
queueing repair process (FASTR), and the single server
queueing repair process (SLOWR). The important items and
explanation of each storage follow. (1) Storage -- the name
used to represent the physical entity. (2) Capacity -- the
maximum number of transactions which can use the storage
at any one time. (3) Average Contents -- the average
number of transactions that were in the storage during the
run. (4) Entries -- the number of transactions which
entered the storage. For SLOWR this is the number of
batches of items that entered the repair process rather
than the number that were repaired as in the FASTR storage.
Likewise, it is the number of orders placed rather than the
number of items ordered for the ORDER storage. (5) Average
Time/Tran -- the average number of hours that an order was
outstanding, or the average number of hours that it took
for an item to be repaired, or the average number of hours
it took for a batch of items to be repaired. (6) Maximum
Contents -- the maximum number of transactions that used
the storage at any time during this run.

c. Queue Statistics

This division reflects the important statistics for the infinite server queue repair department (FSTRQ) and the single server queue repair department (SLOWQ). The important items and explanation of each follow. (1) Queue -- the name used to represent the physical entity. (2) The explanation for maximum contents, average contents, and average time/tran are the same as for storages. (3) Total Entries -- the number of transactions which entered the queue. (4) Zero Entries -- the number of transactions which entered the queue and departed with no time delay. Note that for the FSTRQ it should always be the same as the total entries. (5) Average Time/Trans -- the average number of hours that the delayed transactions, only, spent waiting to be repaired.

2. Standard Output

An example of the standard output is illustrated in Appendix D. Notice that the standard output includes all of the items listed in the summary output as well as the following items. (1) table statistics, (2) group counts, and (3) block counts.

The table statistics provide the statistics of the following tables: BTCHZ, BTIME, ENOH, NBARB, NUMC, and RDYRT. The important items and explanations of each follow. (1) Table -- the name used to collect the particular statistic. (2) Entries in Table -- the number of times that an entry was made in the table. (3) Mean Argument --

the average value of the entries made in the table.

(4) Standard Deviation -- the standard deviation of the
entries made in the table. (5) Upper Limit -- the maximum
value of each cell of the table. For example, all entries
between 51 and 100 fall in cell two of BTIME table.

(6) Observed Frequency -- the number of entries which fall
into this cell. (7) Percentage of Total and Cumulative
Percentage are self-explanatory. (8) Multiple of Mean --
the upper limit of the cell expressed as a multiple of the
mean of the table. The additional pieces of information
given in the tables as well as the queue and storage
statistics which are not explained in detail here are those
which, under normal circumstances, are of no concern to the
user. However, there may be occasions when a user wishes
to make changes internal to the program such as adding the
capability of handling compound Poisson demands. In such
a case the standard output would be a necessity, especially
the block counts, in helping the user debug the program.
The reason this output was included is to show the user
that this additional information is available from the
computer, and to show the user the type of output he will
receive by default should an error be made while using the
model. If the user desires to receive the standard output,
XH17 should be set to one on initial card three. If one
desires further information relating to computer output,
he should see the IBM User's Manual [Ref. 4].

VI. USES AND APPLICATIONS OF THE MODEL

This model was built for three major reasons. First and foremost was to give a convenient and useful tool to present day inventory managers faced with the decisions of how much to buy, when to buy, and how to conduct repairs for the items under their cognizance. As was pointed out earlier, there are presently two major approaches in vogue to help the manager solve his problem; cost analysis and the use of simple procurement policies with specified measures of supply performance. Under the cost analysis approach the user runs into the difficult problems of quantifying costs. For instance I, the inventory holding cost, consists of many things, some of which all managers agree on, such as storage and handling, and some which they don't agree on, such as loss, breakage, and opportunity cost. Similar disagreements concern the fixed order cost as well. For example, the Navy uses a sliding scale from $25 to $75, while the Army uses a different sliding scale from $50 to $400. Further problems arise when one tries to assign a cost to a critical item being out of stock when needed. Primarily because of these difficulties in quantifying costs, the second approach was used in this paper. It was felt that statements such as "a fill rate of 95% must be maintained" would at least mean the same thing to all managers as well as being something that all managers could agree on.

The second reason this model was built was to provide an efficient way of obtaining insight into the problems faced by the inventory manager. Simulation is a straight-forward and logical way of doing this. In addition simulation avoids some of the pitfalls of the more classical means of analysis. For example, the model can use any time-step desired and simulate as far into the future as desired. The model easily handled the different types of repair processes which analytically prove to be quite cumbersome. When these reasons are coupled with the combined effects of uncertainty, dynamic interaction of system events, and interdependence among system parameters, it is easily seen why this problem was particularly amenable to simulation. Richards [Ref. 7] showed that analytical expressions could be obtained for the individual measures of performance used in this paper. However, to actually generate numbers from these expressions for a sensitivity analysis of this size would be a monumental task. Therefore, simulation again seemed to be called for. Also, the advantage of time compression, both in being able to simulate into the future in a matter of seconds and being able to obtain numerical values for the various measures of performance, made simulation appealing.

A major criticism of simulation is that the simulated queueing model yields only an estimate of parameters, such as a waiting line's average length or associated probability of delay, and as such is subject to statistical

error. A second criticism is that if the system is so complicated and complex that the other methods fail and a simulation is required, it will necessarily be a very difficult job to build the model and analyze its results.

In this particular case the first disadvantage acted to a much lesser degree since analytical expressions for all the measures of performance used in this model do exist. This fact allowed less replication to obtain trustworthy answers in the search for the best choices of the policy parameters. A moderate number of runs in a reasonable period of time accompanied with the statistical tests of section four also lent credibility to the answers and conclusions obtained. The second disadvantage noted went for naught since the model exists and works.

Finally, the third reason that this model was constructed was to demonstrate the validity of certain analytical expressions for some of the measures of performance used in this paper. As was pointed out in section four, the model succeeded in doing this. From the comments above and the results presented in this paper, it is easily seen that the model can be used effectively to describe current inventory systems, to explore hypothetical inventory systems, and to design or improve given inventory systems, as well as be used as a teaching aid. The simulation model can be used to help answer such a current question as how to best conduct repairs on the engines for the new class of destroyers DD963.

In applying this model to any of the uses mentioned above, one is always faced with the problem of deciding which measure of performance to use as the criterion for making decisions. In this paper the expected number of unit years of backorders per unit period was used. One reason it was used over the average number of items on backorder per unit period was that it considers both the number of backorders and the amount of time the backorders were outstanding, while the other merely considers the number of backorders, totally ignoring the amount of time the backorders were outstanding. It was felt that both the fill rate and the ready rate were even worse than the average number of backorders since they don't even take into consideration the number of units backordered, but merely note whether or not any backorders exist. Perhaps the most significant reason the expected number of unit years of backorders per unit period was used as the criterion was that once it was considered acceptable, the remaining measures of performance were also acceptable.

There were occasions when another measure of performance, the average number of items on hand at an arbitrary point in time, was used to help determine an optimal operating point for a given system. Such was the case in experiment one when there appeared to be a number of acceptable operating points, (Q,R) pairs, for the system under investigation. This measure of performance was used in these cases to differentiate between these pairs.

As mentioned earlier, this model can also be used as a teaching aid as well as demonstrating analytical results obtained by others. Table XX (page 75) is a good example of this. If one sets the probability of repair equal to one, the model degenerates to the all repairables case without degradation. From the table, one can see how the various measures of performance change as the mean demand during repair time varies. Further, if Q is required to be one, the results of this model can be compared with the results of Feeney and Sherbrooke [Ref. 6]. Notice that in their results the fill rate was always zero when the reorder point was zero. This result was a consequence of their initial conditions, whereas the results obtained by this model do not include that restriction. If we again restrict the model by considering the all consumables case (i.e. letting the probability of repair be equal to zero) the model becomes that described by Hadley and Whitten [Ref. 3]. Using a sample problem, one again has an example of how the model can be used to verify known analytical results. This example and comparison to the cost approach is summarized in Table XXI.

Of course there are endless experiments one could carry out with the use of this model. For instance one could use this model to help decide which items should be designated repairable. This could be done by comparing the measures of performance obtained by considering an item first as a consumable and then as a repairable. It would also be easy

TABLE XX. COMPARISON BETWEEN FEENEY & SHERBROOKE'S [REF. 6] RESULTS WITH THIS SIMULATIONS RESULTS

$\overline{X}$=MEAN DEMAND DURING REPAIR TIME   Q=1, K=1, L=0

F(S)=FILL RATE   R(S)=READY RATE   P=1.0 (all repairables)

| REORDER POINT R | $\overline{X}=2.5$ | | | | $\overline{X}=.50$ | | | | $\overline{X}=1.00$ | | | |
| | F&S | | SIM | | F&S | | SIM | | F&S | | SIM | |
	F(S)	R(S)	F(S)	R(S)	F(S)	R(S)	F(S)	R(S)	F(S)	R(S)	F(S)	R(S)
0	0	77.9	75.3	81.5	0	60.6	65.3	56.7	0	36.8	39.2	34.1
1	57.8	97.4	99.2	97.6	60.7	90.9	91.0	89.3	36.7	73.6	70.7	73.4
2	97.4	99.8	100	99.4	91.0	98.6	98.4	98.8	73.6	91.9	91.4	92.9
3	99.8	99.9	100	100	98.6	99.8	100	99.4	91.9	98.1	98.2	97.6
4	100	100	100	100	99.8	100	100	100	98.1	99.6	100	100
5	100	100	100	100	100	100	100	100	100	100	100	100
%	%	%	%	%	%	%	%	%	%	%	%	%

TABLE XXI. COMPARISON BETWEEN HADLEY & WHITTEN [REF. 3] WITH THIS SIMULATION

Q=32, MEAN TIME BETWEEN DEMANDS = 3504 hours   P=0.0 (all consumables)

	H&W	SIM
R	32	26
B_T	0	0

to extend this model to make use of the variance reduction
techniques explained in reference nine or to add the
capability of handling compound Poisson demands.

VII.   SUMMARY AND CONCLUSION

The analysis of the repairable inventory problem pre-
sented in this paper was based upon a simulation model
thought to be sufficiently realistic and general enough to
represent many different inventory systems.

The results have shown that the simulation can be a
helpful tool for the managers of inventory systems to use
to make wise decisions governing their policies concerning
when and how much to reorder. It was demonstrated in this
paper that the mean time to repair an item, but not the
repair time distribution itself, was extremely critical to
system performance. It was demonstrated, at least for
systems with a mean repair time less than or equal to 1.4,
that a constraint placed on the minimum repair batch size
had a negligible effect on system performance. It was
further demonstrated for this same system that reducing
the mean repair time by 40% was more profitable than doubling
the maximum repair batch size. It also demonstrated that
increasing maximum repair batch size beyond those values
which gave a service rate of .417 or less had negligible
effect in terms of increasing system performance. This
paper also emphasized the power of using the expected
number of unit years of backorders per unit period as the

criterion for judging system performance. This measure, when reduced to an acceptable level, was accompanied by good values of all other measures of performance as well. This is not true of the other measures. For example, if the fill rate had been used, Table XIII shows that an acceptable fill rate doesn't necessarily imply that all the other measures of performance are also acceptable.

It is believed that this paper supplements the tools which are needed to make intelligent decisions concerning the repairable item inventory system. Of course it can also be used for the consumables case by merely setting the probability of repair equal to zero.

A couple of further remarks seem to be in order. First, it would seem worthwhile to determine if current repair departments could be utilized more fully. Perhaps this could be achieved by spending a greater fraction of budget dollars to repair available carcasses rather than continuing to procure new material. Secondly, this study seems to indicate that study of a stock point's physical plant for repairables could be profitable. For example, the fourth experiment indicated that the minimum repair batch size required before repair begins on a batch of items could fluctuate to some degree before system performance is degredated.

Much has been learned about the interrelationships and effects of many of the parameters of repairable and non-repairable inventory systems. Perhaps this has been the

most significant result of the project. It would seem impossible for anyone who would work with this simulation not to come away with a better understanding of the hidden mechanisms and inner workings of an inventory system.

In closing, a simulation model for continuous review inventory systems was presented. The model used, demonstrated the sensitivity of Q, R, K, and L to numerous operational constraints and system parameters. A class of simple policies with various measures of performance was used rather than a traditional cost postulated model to determine acceptable parameters for a given inventory system. It is felt that the model can be successfully implemented in a very large number of inventory problems.

APPENDIX A. STATISTICAL TESTS

Analysis of variance. This test was used to find the significant difference in observed values of the expected number of unit years of backorders per unit period.

	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio
Between groups	436.3584	11	39.6689	194.0706
Within groups	18.8052	92	0.2044	
Total	455.1636	103		

Table value from F-Distribution for 92 and 11 degrees of freedom at .01 significance level = 2.48.

194.0706 > 2.48, therefore the null hypothesis was rejected.

Null hypothesis: The observed values for the expected number of unit years of backorders per unit period are the same for each treatment (reorder point value).

K. A. Scheffe's Multiple Comparison Test. This test
was used to find the magnitude required for the expected
number of unit years of backorders per unit period to be
significantly different from zero.

If

$$\frac{(\,|C_j|\,)^2}{(N-1)(\hat{V}\,(C_j)\,)} > F_{(1-\alpha)(n_1)(n_2)}$$

then the hypothesis that the contrast C_j differs from
zero is rejected.

$$C_j = \sum_{i=1}^{t} C_{ij}\,T_i\;.$$

$\hat{V}\,(C_j)$ is the estimated variance of contrast C_j.

$\hat{V}\,(T_i)$ is the estimated variance of the ith treatment$=S^2$.

T_i is the sum of the n_i observations for the ith treatment.

S^2 is the mean square of the experimental error.

t is the number of treatments included in contrast C_j.

C_{ij} are the coefficients for the jth comparison with the ith treatment.

α is the significance level chosen$=.01$ for this particular test.

$N-1$ is the total number of treatments less one.

$(n_1)(n_2)$ are the degrees of freedom.

Let C_1 be the contrast between (QR) pairs (10,11) and (10,10) respectively. Then:

$$C_1 = C_{10,1}T_{10} + C_{11,1}T_{11} = (3)(-25.3176) + (-4)(-22.1442) = 12.62$$

$$\hat{V}(C_1) = \sum_{i=10}^{11} C_{i1}^2 (T_i) = (3^2)(8)(.2044) + (-4)^2(6)(.2044) = 34.339$$

$$\frac{(|C_1|)^2}{(N-1)(\hat{V}(C_1))} = \frac{(12.62)^2}{(11)(34.339)} = .422$$

$.422 \not> 2.48$ therefore, H_o is not rejected.

Let C_2 be the contrast between (QR) pairs (10,11) and (10,9) respectively. Then:

$$C_2 = C_{9,2}T_9 + C_{11,2}T_{11} = (4)(22.404) + (-6)(-22.1442) = 43.24$$

$$\hat{V}(C_2) = (4^2)(9)(.2044) + (-6)^2(6)(.2044) = 73.584$$

$$\frac{(|C_2|)^2}{(N-1)(\hat{V}(C_2))} = \frac{(43.24)^2}{(11)(73.584)} = 2.309 \qquad \begin{array}{l} 2.309 \not> 2.48 \\ \text{Therefore, } H_o \\ \text{is not} \\ \text{rejected.} \end{array}$$

Let C_3 be the contrast between (QR) pairs (10,11) and (10,8) respectively. Then:

$$C_3 = C_{8,3}T_8 + C_{11,3}T_{11} = (4)(-14.353) + (-6)(-22.1442) = 75.453$$

$$\hat{V}(C_3) = (4)^2(9)(.2044) + (-6)^2(6)(.2044) = 73.584$$

$$\frac{(|C_3|)^2}{(N-1)(\hat{V}(C_3))} = \frac{(75.453)^2}{(11)(73.584)} = 6.994 \qquad \begin{array}{l} 6.994 > 2.48 \\ \text{Therefore,} \\ \text{reject } H_o, \text{ the} \\ \text{null hypothesis} \\ \text{that the means} \\ \text{are equal.} \end{array}$$

Let C_m be the contrast between (QR) pairs (10,11) and (10,m) respectively. Then:

$$\frac{(\,|C_m|\,)^2}{(N-1)(\hat{V}(C_m))} = 2.48 = (|C_m|)^2 = (2.48)(11)(73.584) =$$
$$2007.372$$

$C_m = 44.8$ (minimum contrast value required for statistical significance.)

Then: $44.8 = C_{x,m}T_x + C_{11,m}T_{11} = (4)T_x + (-6)(22.404)$

$T_x = 22.016$

$\log_e B_T = -2.450$

$B_T = .086$ the significant difference of the expected number of unit years of backorders from .01

$B_T = .01 + .086 = 0.096$ the minimum significant difference from zero

83

This completes the main part of the model.

84

85
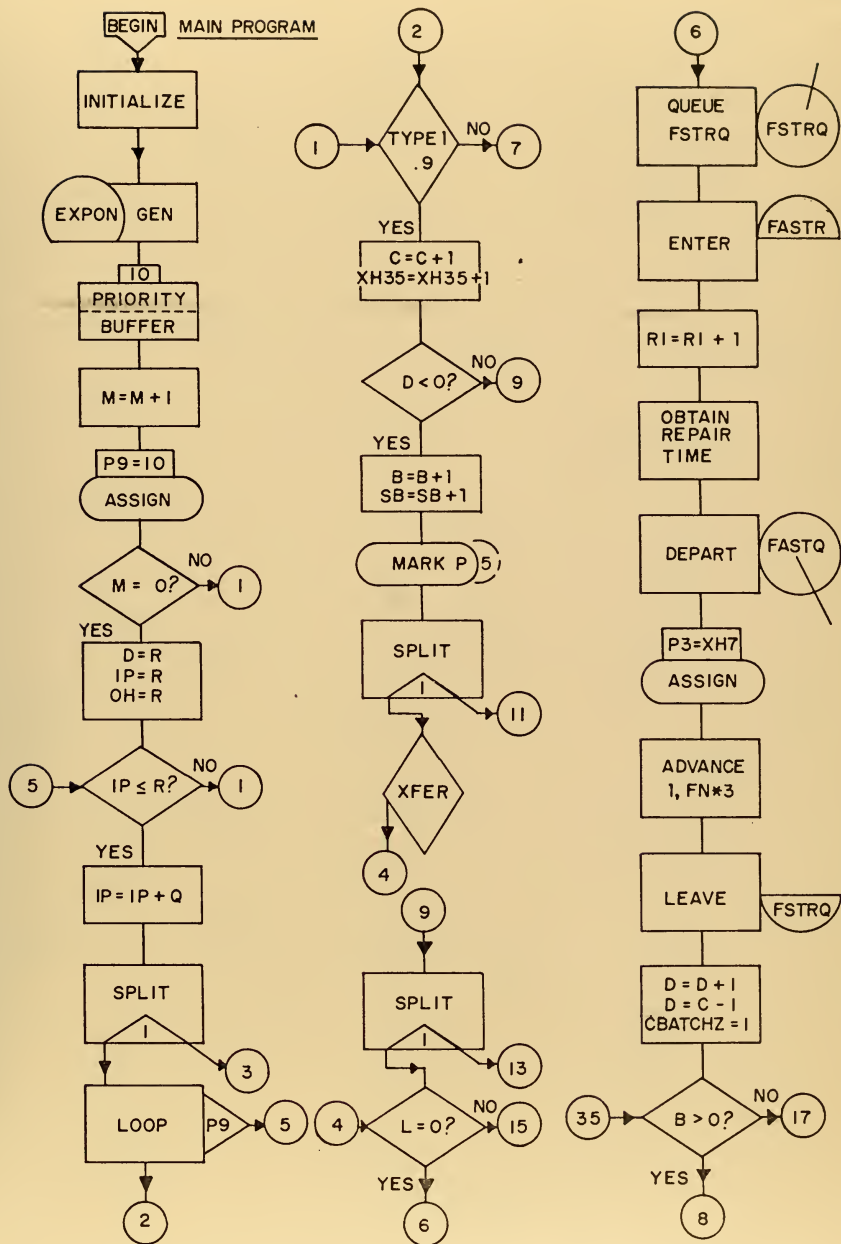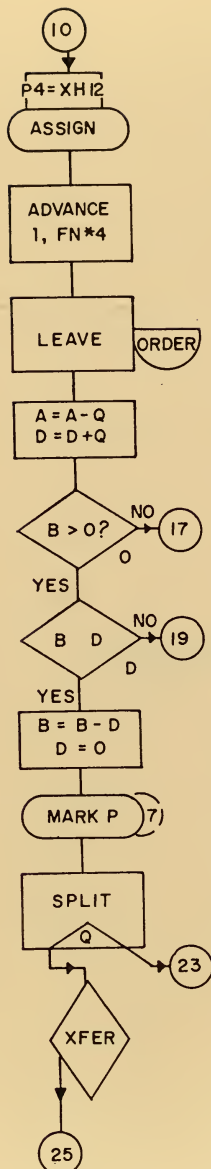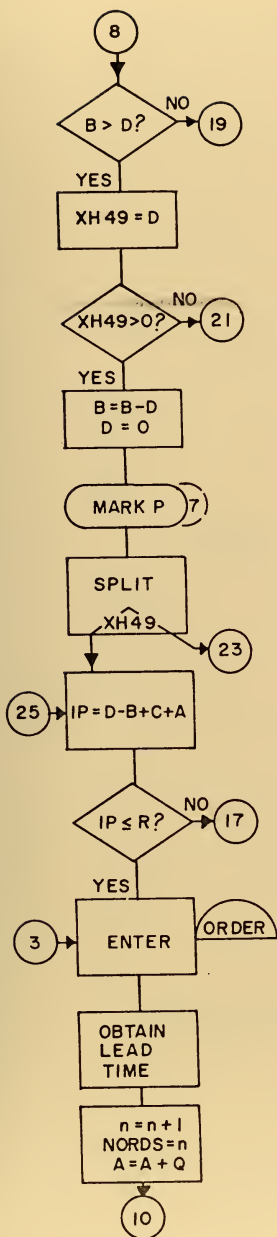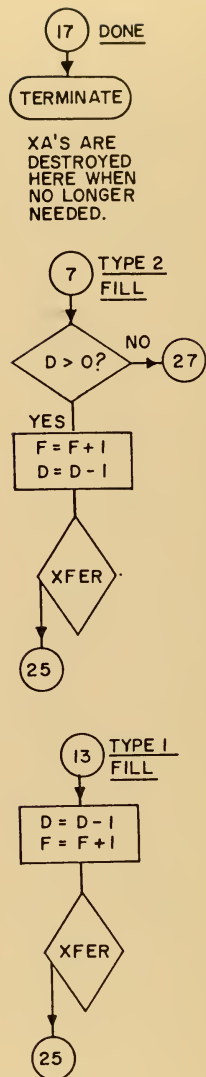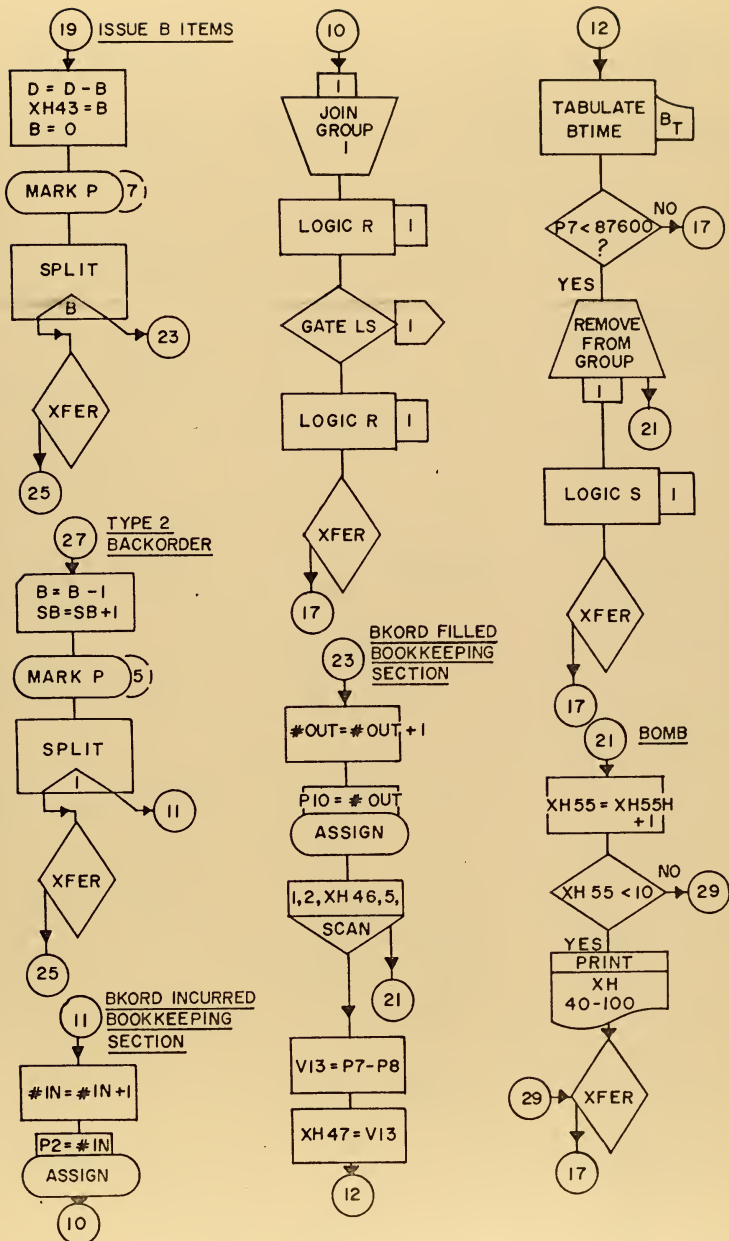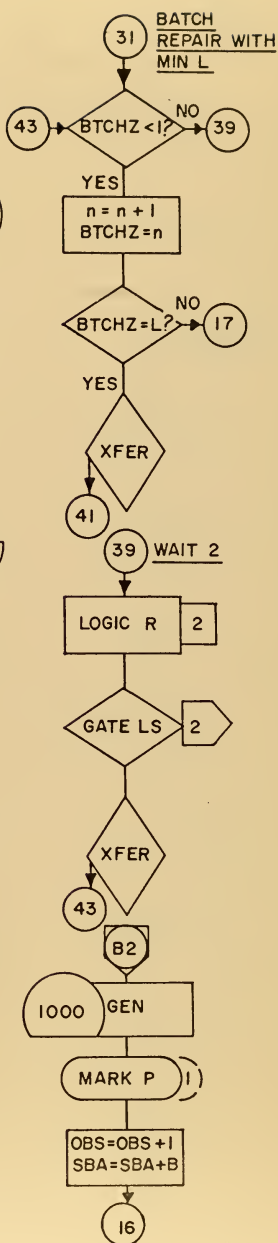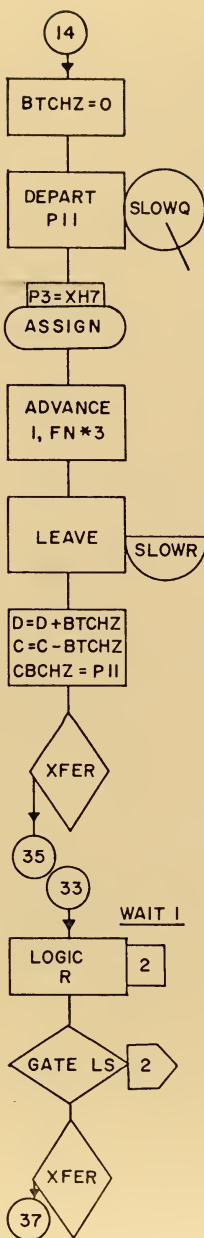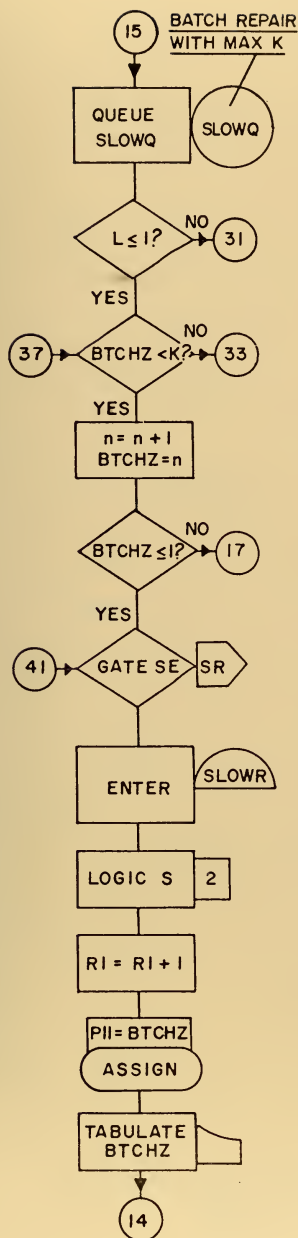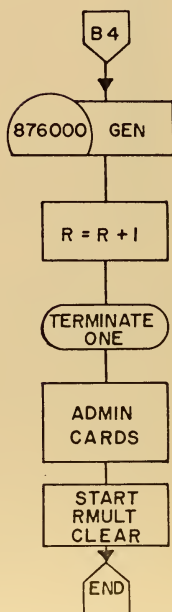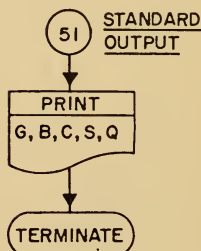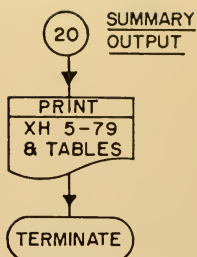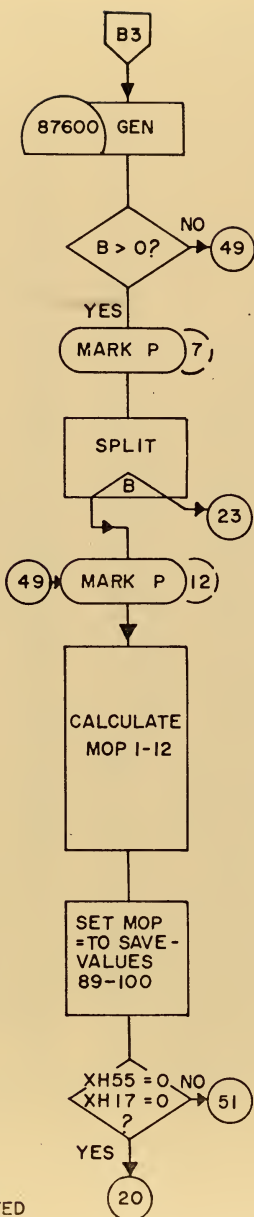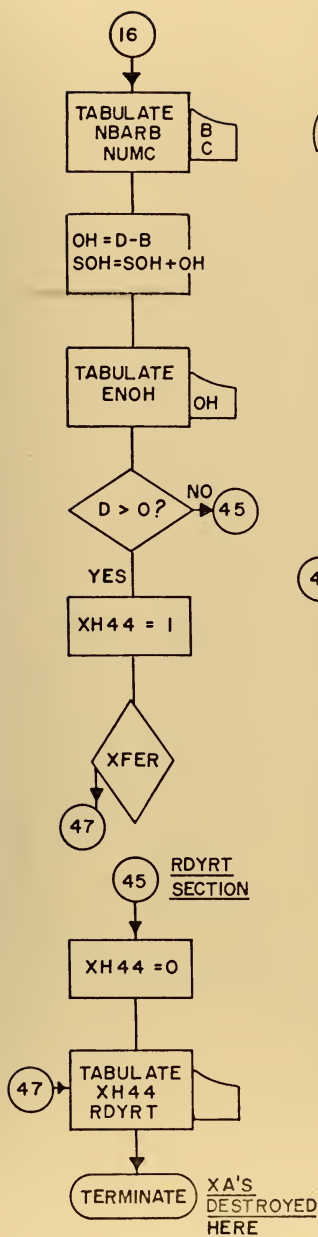
APPENDIX C   Program Listing

```
//THESIS PROGRAM DECK
//JOBLIB DD DSNAME=GPSS,DISP=SHR
//EXEC GPSS
//DOUTPUT DD    SPACE=(CYL,8)
//GO.DINTERO DD    SPACE=(CYL,(1,1))
//GO.DSYMTAB DD    SPACE=(CYL,(1,1))
//GO.DREPTGEN DD    SPACE=(CYL,(1,1))
//GO.SYSIN DD *
        REALLOCATE BLO,200,FAC,0,STO,4,QUE,3,LOG,2,FUN,12,VAR,20
        REALLOCATE FSV,5,HSV,100,CHA,0,BVR,0,FMS,0,HMS,0,COM,42600
        INITIAL    TAB,06,GRP,1,XAC,500
        INITIAL    XH1,10/XH2,01/XH3,0/XH4,001/XH5,0900/XH6,061/XH7,5
        INITIAL    XH8,336/XH9,168/XH10,504/XH11,095/XH12,10/XH13,504
        INITIAL    XH14,240/XH15,768/XH16,088/XH17,0
        SIMULATE
        RMULT      63785,32523,51497,20613,43315,13185,81207,96311
        GOING CONCERN

*   A PROBABILISTIC EVENT STORE COMPUTER SIMULATION OF THE INTERACTIONS
*   OF VARIOUS PARAMETERS OF A SINGLE ECHELON, CONTINUOUS REVIEW, QR,
*   REPAIRABLE ITEM INVENTORY SYSTEM.

*   THE PURPOSE OF THIS MODEL IS TO TEST AND INVESTIGATE THE SESITIVITY OF
*   THE PARAMETERS INVOLVED TO HELP THE DECESION MAKER EVALUATE OR SET UP
*                          AN INVENTORY SYSTEM.
*   UNITS: ONE TIME UNIT = ONE HOUR. ONE UNIT PERIOD EQUALS 10 YEARS OF OP

EXPON FUNCTION RN8,C24
0,0/.1,.104/.2,.222/.3,.355/.4,.509/.5,.69/
.6,.915/.7,1.2/.75,1.38/.8,1.6/.84,1.83/.88,2.12/
.9,2.3/.92,2.52/.94,2.81/.95,2.99/.96,3.2/.97,3.5/
.98,3.9/.99,4.6/.995,5.3/.998,6.2/.999,7.0/.9997,8.0/
RNTIM FUNCTION RN2,C2
0,0/1.0,1.0
3 FUNCTION RN4,E2              CONSTANT REPAIR TIME
0.5,XH8/1.0,XH8
4 FUNCTION RN4,E2              UNIFORM DISTN FOR REPAIR TIME
0.5,XH036/1.0,XH036
5 FUNCTION RN4,E2              NORMAL DISTN FOR REPAIR TIME
0.5,XH037/1.0,XH037
6 FUNCTION RN4,D10             EMPERC DISTN FOR REPAIR TIME
0,20,.215/.40,.230/.50,.250/.60,.290/
.90,.504/.95,.515/.99,.530/.995,.540/.999,590/
7 FUNCTION RN3,E2              CONSTANT LEAD TIME.
0.5,XH13/1.0,XH13
8 FUNCTION RN3,E2              UNIFORM DIST'N FOR LEAD TIME.
0.5,XH038/1.0,XH038
```

2
13
4
600
200
300
500
600
800
900
100
160
180
180
190
200
210
230
240
260
280
2805
2295
300
320
330

```
         9 FUNCTION   RN3,E2          NORMAL DIST'N FOR LEAD TIME.
0.5,XH039/1.0,XH039
        10 FUNCTION   RN3,D10         EMPERCL DIST'N FOR LEAD TIME.
0.06,439/0.07,439/0.08,439/0.58,464/0.66,486
0.68,558/C.69,558/0.71,558/0.96,594/1.0,680
UNFMZ FUNCTION   RN3,C2
0.0/1.0,100
NORMZ FUNCTION   RN3,C69
0.0003,-340/0.0005,-320/0.0007,-310/0.0010,-300/0.0013,-300/0.0019,-290/
0.0026,-280/0.0035,-270/0.0047,-260/0.0062,-250/0.0082,-240/0.0107,-230/
0.0139,-220/0.0179,-210/0.0228,-200/0.0287,-190/0.0359,-180/0.0446,-170/
0.0548,-160/0.0668,-150/0.0808,-140/0.0968,-130/0.1151,-120/0.1357,-110/
0.1587,-100/0.1841,-90/0.2119,-80/0.2420,-70/0.2743,-60/0.3085,-50/
0.3446,-40/0.3821,-30/0.4207,-20/0.4602,-10/0.5000,0/
0.5398,10/0.5793,20/0.6179,30/0.6554,40/0.6915,50/0.7257,60/
0.7580,70/0.7881,80/0.8159,90/0.8413,100/0.8643,110/0.8849,120/
0.9032,130/0.9192,140/0.9332,150/0.9452,160/0.9554,170/0.9641,180/
0.9713,190/0.9772,200/0.9821,210/0.9861,220/0.9893,230/0.9918,240/
0.9938,250/0.9953,260/0.9965,270/0.9974,280/0.9981,290/0.9987,300/
0.9990,310/0.9993,320/0.9995,330/0.9997,340/
*
         GENERATE   XH6,FN$EXPON,,,8,,F   GENERATE DMNDS IAW PDISS DISTBN
         PRIORITY   10,BUFFER             ASSIGN HIGH PRI TO XA BEING PROCESSED
         ASSIGN     079+,1,H              DMDS=DMDS+1, TOT NUM OF DMDS T PERD
                 9,10
ONE      TESTE      XH079,1,SPCT          IF THIS ISN'T 1ST DMD GO TO SPCT
         SAVEVALUE  074+,XH2,H            IF THIS IS FIRST DEMAND SET D=R
         SAVEVALUE  070+,XH2,H            IF THIS IS FIRST DEMAND SET IP=R
         SAVEVALUE  057,XH2,H             IF THIS IS FIRST DEMAND SET OH=R
         TESTLE     XH070,XH2,SPCT        IF IP>R XFER XA TO SPCT DON'T ORDER
         SAVEVALUE  070+,XH1,H            IF IP<=R ORDER Q ITEMS. IP=IP+Q
         SPLIT      1,WEORD               IF WEORD,SEND XA TO ORDER SECTION
         LOOP       9,ONE                 GO AND TEST IP LEVEL AGAIN.
SPCT     TRANSFER   .XH5,TYPE2,TYPE1      INSPECT TO SEE IF ITEM TYPE 1 OR 2
*****
         THESE ARE TYPE ONE ITEMS (REPAIRABLE ITEMS).
TYPE1    SAVEVALUE  073+,1,H              C=C+1 C=NUM OF ITEMS IN REPAIR NOW.
         SAVEVALUE  35+,1,H               #TYPE 1= #TYPE 1+1.
         TESTLE     XH074,0,NEX1          IF D>0 DON'T BACKORDER. GO TO NEX1
****
                 SINCE D=0,BACKORDER
         SAVEVALUE  071+,1,H              B=B+1 B=NUM OF ITEMS BCKORDERED NOW
         SAVEVALUE  098+,1,H              SB=SB+1 SB=TOT NUM OF B THIS YR.
```

```
        MARK                                  RECORD TIME BACKORDER PLACED.         770
        SPLIT      5,GRUP1                     SEND XA TO B BOOKEEPING SECTION       780
        TRANSFER   1,?REPAR                    D=0 SO BYPASS COMAND TO GO TO ISSUE   790
        SPLIT      1,ISUE1                      SEND XA TO ISSUE DEPT.               800
NEX1    SPLIT                                                                        810
REPAR   TEST E     XH3,0,BATCH                  IF L>0 SEND XA TO BATCH REPAIR DEPT  820
****                                                                                 830
L=0,K=1 => INFINITE SERVER QUEUE SYSTEM, (REPAIR ONE AT A TIME FIFO).                840

        QUEUE      FSTRQ                         ITEM ENTERS REPAIR DEPT QUEUE.       860
        ENTER      FASTR                         ITEM ENTERS REPAIR DEPT. THIS PERIOD 870
        SAVEVALUE  XH076+,1,H                    RI=RI+1;NUM OF REP IND. THIS PERIOD  880
UUFMX   FVARIABLE  036,V$UUFMX,H                 XH36=RANDOM UNIFORM REPAIR TIME      890
        SAVEVALUE  XH08+((XH11*FN$NRMLX,H        XZ=U+(STD DEV)*Z                     900
NRMLX   FVARIABLE  037,V$NRMLX,H                 XH037=RANDOM NORMAL REPAIR TIME.     910
        DEPART     FSTRQ                                                              920
        ASSIGN     3,XH7                         ASS TYPE OF REP TIME DIST'BN TO P3   930
        ADVANCE    1,FN*3                        REPAIR ITEM.                         940
        LEAVE      FASTR                         ITEM LEAVES. REP DEPT.               945
        SAVEVALUE  074+,1,H                      D=D+1 D=NUM READY FOR ISS NOW.       950
        SAVEVALUE  073-,1,H                      C=C-1                                960
        SAVEVALUE  049,1,H                        CBATCHZ = 1                         970
                                                                                     980
ITEM(S) HAVE RETURNED FM REP DEPT.CHECK IF ISS NECESSARY.                            990
ISUE2   TEST G     XH071,0,DONE                  IF B=0 KILL XA.                     1000
                                                                                    1010
*****                                                                               1020
B>0, AN ISS WILL FOLLOW.                                                            1030
***                                                                                 1040
        TEST GE    XH071,XH074,ISS/B            IF B<D ISS B ITEMS SEND XA TO ISS/B 1050
                                                                                    1060
B IS > OR = TO D, ISSUE D ITEMS                                                     1070
***                                                                                 1080
        SAVEVALUE  049,XH074,H                   RECORD NUM OF ITEMS ISS IN XH49.    1090
        TESTGE     XH049,0,BOMB                  IF D<V 0 AN ERROR IN INPUT HAS OCCR 1100
        SAVEVALUE  071-,XH074,H                  B=B-D.                             1104
        SAVEVALUE  074,0,H                        D=0.ISSUE C ITEMS                 1110
        MARK       7                             RECORD TIME THESE D BKORD'S FILLED 1120
        SPLIT      XH049,GROP1                    SEND D XA'S TO B BOOKEEPING SECT.  1130
                                                                                    1140
*****                                                                               1145
AN ISS AND/OR B OCCURRED, IS A REORDER NECCESSARY ?                                 1150
ORDER   ADVANCE    0                                                                1160
1       VARIABLE   XH074-XH071+XH073+XH072      V1=IP=D-B+C+A                       1170
```

```
*** TEST LE      V1,XH2,DONE         IF IP>R KILL XA.                                    1200
                 IP < OR = R A REORDER IS NECESSARY,                                     1205
WEORD  ENTER     ORDER               ENTER ORDER DEPT.                                   1210
UNFMX  FVARIABLE XH14+((XH15-XH14)*FN$UNFMZ)/100)  RANDOM UNIFORM LEAD TIME              1220
NORMX  SAVEVALUE O38,+,V$UNFMX,H     X=U+(STD DEV)Z.                                      1230
       FVARIABLE XH13+((XH16*FN$NORMZ)/100)        NORMAL LEAD TIME                       1240
       SAVEVALUE O39,+,V$NORMX,H     NORDS=NORDS+1. THE # OF ORDS T RUN.                 1250
       SAVEVALUE 075+,1,H                                                                 1260
       ASSIGN    072+,?,XH1,H        A=A+Q  A=NUM ON ORDER NOW.                          1270
       ADVANCE   4,FN*4              ASS'Y TYPE Q ITEMS. NORMAL LEAD TIME DIST'BN TO P4. 1280
       LEAVE     ORDER               RECEIVE ORDER.                                       1290
       SAVEVALUE 072-,,XH1,H         A=A-Q.                                               1300
       SAVEVALUE 074+,,XH1,H         D=D+Q.                                               1310
                                                                                         1320
                                                                                         1330
                                                                                         1340
**** AN ORDER HAS BEEN RECEIVED CHECK TO SEE IF AN ISS IS REQUIRED.                      1355
       TEST G    XH071,0,DONE        IF B=0, KILL XA.                                    1360
***    B>0, AN ISS WILL FOLLOW.                                                          1365
       TEST GE   XH071,XH074,ISS/B   IF B<D ISS B ITEMS.SEND XA TO ISS/B.               1370
***    B > OR = D, ISSUE D ITEMS.                                                         1380
       SAVEVALUE 071-,,XH074,H       B=B-D.                                               1390
       SAVEVALUE 074-,0,H            D=0.ISSUE D ITEMS.                                   1400
       MARK      7                   RECORD TIME THESE D.BKORD'S FILLED                  1410
       SPLIT     XH1,GROP1           SEND D XA'S TO B BOOKEEPING SECTION.               1420
       TRANSFER  .ORDER              CHECK TO SEE IF REORD NECESSARY                     1430
       TERMINATE                     XA'S ARE KILLED HERE.                               1440
DONE                                                                                     1450
THIS COMPLETES THE MAIN PART OF THE MODEL                                                1460
**********                                                                               1470
                                                                                         1480
              THE BRANCHES FROM THE ABOVE PROGRAM FOLLOW                                 1490
                                                                                         1500
                                                                                         1510
***  THIS IS A TYPE2 ITEM (NON REPAIRABLE) SEE IF WE CAN FILL DEMAND.                    1520
TYPE2  TEST G    XH074,0,BKORD       IF D=0 SEND XA TO BKORD SECTION                     1530
**                                                                                       1535
```

```
****                    D>O WE CAN FILL DEMAND IMMEDIATELY.

        SAVEVALUE  077+,1,H    FILL DEMAND (ISS ITEM)., F=F+1.
        SAVEVALUE  074-,1,H    D=D-1.
        TRANSFER   ,ORDER      IS A REORDER NEC? SEND XA TO ORDER

*** TYPE 1 ITEM WITH   D>O WE CAN FILL DEMAND IMMEDIATELY.

ISUE1   SAVEVALUE  074-,1,H    ISSUE ITEM.
        SAVEVALUE  077+,1,H    F=F+1,F=NUM OF FILLS THIS RUN,
        TRANSFER   ,ORDER      IS A REORDER NEC? SEND XA TO ORDER

*** AN ORDER OR REPAIRED ITEM WAS RECEIVED AND B<D SO ISSUE B ITEMS.

ISS/B   SAVEVALUE  074-,XH071,H   D=D-B.
        SAVEVALUE  043,XH071,H     RECORD # OF ITEMS RECEIVED IN XH43
        SAVEVALUE  071,0,H         B=0.
        MARK       7               RECORD TIME B BRORD'S FILLED.
        SPLIT      XH043,GROP1     SEND B XA TO B BOOKEEPING SECTION
        TRANSFER   ,ORDER          CHECK TO SEE IF REORD NECESSARY.

****  TYPE 2 DEMANDS WITH D=0 SO THEY ARE BACKORDERED.

BKORD   SAVEVALUE  071+,1,H    B=B+1
        SAVEVALUE  098+,1,H    SB=SB+1, SB=NUM B THIS YR.
        MARK       5           RECORD TIME OF B.
        SPLIT      1,GRUP1     SEND XA TO B BOOKEEPING SECTION.
        TRANSFER   ,ORDER      CHECK TO SEE IF REORD NECC

**** BACKORDER INCURRED BOOKEEPING SECTION

GRUP1   SAVEVALUE  045+,1,H    #IN=#IN+1, # OF B INCURRED THIS RUN
        ASSIGN     2,XH045     INDEX=X, BACKORDERS.
        JOIN       1           FLAG XA AS BEEING B.
        LOGIC R    1           RESET GATE SO B WAITS TIL FILLED
        GATE LS    1           ALLOW XA THROUGH IF B FILLED
        LOGIC R    1           CLOSE GATE, NEXT B WAITS TIL FILL
        TRANSFER   ,DONE

**** BACKORDER FILLED BOOKEEPING SECTION
```

1590
1595
1596
1600
1610
1620
1635
1636
1640
1650
1660
1670
1680
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1965
1970
1980

```
GROP1 SAVEVALUE 046+1,H         #OUT=#OUT+1,# OF B FILED THIS RUN    1990
*                                                                   1995
      ASSIGN    10,XHO46        ASSIGN INDEX OF FILLED B TO P10.     2000
      SCAN      1,2,XHO46,5,8,BOMB  GET OLDEST B AND PUT TIM B IN P8 2005
****                                                                2010
      IF NO B FOUND WITH THIS INDEX THERE IS AN ERROR SO BOMB       2020

13    VARIABLE  P7-P8           FIND TIME THIS B OUTSTANDING         2040
      SAVEVALUE 047,V13,H       RECORD TIME IN XHO47.               2050
      TABULATE  BTIME           TIME IN TABLE BTIME.                2060
      TEST L    P7,87600,DONE   IF P7=87600,KILL XA                 2070
      REMOVE    1,,2,XHO46,BOMB REMOVE THIS,B FROM GRUP 1.          2080
      LOGIC S   1               B FILLED, SO OPEN GATE IN GRUP 1    2090
      TRANSFER  ,DONE                                               2110

**                                                                  2120
      IF A XA GETS HERE YOU HAVE MADE AN ERROR IN YOUR INPUT, CHECK IT.   2140

BOMB  SAVEVALUE 055+1,H         BOMB=BOMB+1 BOMB=NUM OF ERRORS.     2170
      TEST L    XH55,10,GETOT                                       2180
      PRINT     40,100,XH,D                                         2190
GETOT TRANSFER  ,DONE           KILL XA                             2200

** THIS SECTION HANDLES THE BATCH REPAIR CASE.                      2215
**                                                                  2216
BATCH ADVANCE  0                ITEM ENTERS REPAIR DEPT             2220
      QUEUE    SLOWQ            IF WE REQ MIN BATCHES GO TO MINBZ   2240
      TEST LE   XH3,1,MINBZ                                         2250
*                                                                   2260
      BATCH REPAIR, K>1,L=1 (RESTRICTION ON MAX BTCHZ ONLY)         2270
      IF L=1 & K=1 THIS IS A ONE SERVER QUEUE REPAIR OPERATION WITH 2280
      ONLY ONE ITEM BEING REPAIRED AT A TIME.                       2290

RULE1 TEST L    XHO48,XH4,WAIT1  IF BTCHZ=K & REP DEPT BUSY,WAIT1   2300
      SAVEVALUE 048+1,H          BTCHZ=BTCHZ+1                      2310
      TEST LE   XHO48,1,DONE      IF BTCHZ>1 KILL XA                2320

****                                                                2335
      THIS ENSURES ONLY ONE XA ENTERS REP DEPT WHILE XHO48(BTCHZ)   2350
      IS.(L-1) < BTCHZ < (K+1))                                     2360

RULE3 GATE SE   SLOWR           IF REP DEPT IDLE,ENTER;ELSE WAIT    2370
      ENTER     SLOWR           BEGIN REPAIR ON NEW BATCH           2380
      LOGIC S                   NEX BTCH IN REP DEPT.               2390
      SAVEVALUE 076+1,H         NUMRI=NUMRI+1 # OF REPAIR INDUCTS   2400
      ASSIGN    11,XHO48         P11=CURRENT BATCH SIZE (BTCHZ)      2410
      TABULATE  BTCHZ           RECORD BTCHZ                        2420
```

```
                              SET BTCHZ = 0
      SAVEVALUE  048,0,H          ASS TYPE OF REP TIME DIST'BN TO P3
      DEPART     SLOWQ,P11        REPAIR ITEM LEAVES REPAIR DEPT
      ASSIGN     3,FN*3           ITEM LEAVES REPAIR DEPT
      ADVANCE    1,FN*3
      LEAVE      SLOWR            D=D+BTCHZ(P11)
      SAVEVALUE  074+,P11,H       C=C-BTCHZ(P11)
      SAVEVALUE  073-,P11,H       CBCHZ=P11=NUM OF ITEM RET'ED EX REP
      TRANSFER   049,P11,H        BATCH RECEIVED,SEE IF WE ISSUE.
                 ,ISUE2

*         REP DEPT BUSY & THE NEX BTCH=K SO THESE ITEMS MUST WAIT
*             TIL THE REP DEPT IS FREE BEFORE FORMING A NEW BATCH

WAIT1 LOGIC R    2                REP DEPTBUSY& NEX BTCHZ=K SO WAIT
      GATE LS    ,RULE1           NEX BTCH IN REP DEPT,FORM NEW BTCH
      TRANSFER                    REP DEPT FREE,FORM NEXT BATCH

*****

*         MINBZ REPAIR, K>1, L>1 (MIN & MAX REQ ON BTCHZ)

MINBZ ADVANCE   0                 IF BTCHZ=K & REP DEPT BUSY, WAIT2
RULE2 TEST L    XH048,XH4,WAIT2   BTCHZ=BTCHZ+1
      SAVEVALUE 048+,1,H          IF BTCHZ > OR=L, KILL XA
      TEST E    XH048,XH3,DONE        IF BTCHZ=L,OR L=K SEE IF REP FREE
      TRANSFER  ,RULE3

*         REP DEPT BUSY & THE NEX BTCHZ=K SO THESE ITEMS MUST WAIT
*             TIL THE REP DEPT IS FREE BEFORE FORMING A NEW BATCH

WAIT2 LOGIC R    2                REP DEPT BUSY&NEX BTCHZ=K SO WAIT2
      GATE LS    ,RULE2           NEX BTCH IN REP DEPT,FORM NEW BTCH
      TRANSFER                    REP DEPT FREE,FORM NEXT BATCH

*******

*         THIS COMPLETES THE BATCH REPAIR PART OF THE MODEL

*         NOW COMPUTE THE RANDOM OBS TIMES AND TABULATE OBS,BA,C,AND OH.

      GENERATE  1000,FN$RNTIM,,,,F  CREATE RANDOM OBSERVATION TIMES.
      MARKVALUE 1                RECORD TIME FOR NEXT OBS IN P1.
      SAVEVALUE 059+,1,H         SOBS=SOBS+1,SOBS=NUM OF OBS IN THIS YR.
      SAVEVALUE 056+,XH071,H     SBA=SBA+B, SBA=NUM OF BA THIS YR.
6     VARIABLE  XH71*100
      SAVEVALUE 54,V6,H
```

```
          7   TABULATE    NBARB
              VARIABLE    XH73*100
              SAVEVALUE   53,V7,H
          2   VARIABLE    NUMC                    RECORD BA, BA=NUM OF B NOW.
              SAVEVALUE   058,V2,H
              TABULATE    (XHO74-XHO71)*100       RECORD C, NUM IN REPAIR DEPT NOW.
              TEST E      ENOH                    V2=OH=D-B  NUM ON HAND NOW.
              SAVEVALUE   XHO74,0,MOVE            SOH=SOH+OH, SOH=#CH THIS RUN*100.
              TRANSFER    044,10000,H             RECORD #*ON HAND NOW.
              SAVEVALUE   044,0,H                 IFD=0 SEND XA TO MOVE
MOVE          TAB                                 SEND XA TO TAB BLOCK
TAB           TABULATE    RDYRT                   IFD=0,XHO44=0
                                                  TAB XH44,XH44=1 IF D > 0, 0 IF D=0

              TERMINATE                  THIS COMPLETES THE TABULATION PHASE.

**  ****

CONTROL OF RUNNING TIME AND CALCULATION OF MEASURES OF PERFORMANCE.

              GENERATE    87600,,,5,,F
              TEST G      XH71,0,NOBL             IF B>0 RECORD TIME THESE B OUTSTDG
              MARK        7                       TIME = 87600
              SPLIT       XH71,GROP1              SEND XA TO BKORD FILLED SECTION
NOBL          MARK        12                      RECORD TIME OF THIS TABULATION
              VARIABLE    001,P12                 RECORD TIME OF TABULATION
          3   FVARIABLE   XHO74-XHO71+XHO73+XHO72  V1=IP=D-B+C+A
              SAVEVALUE   070,V3,H
          5   FVARIABLE   XH2+(XH1+1)/2-(XH5/1000)*(1/XH6)*XH8)*100
          4   FVARIABLE   V5-(1-XH5/100)*(1/XH6)*XH13)*100
              FVARIABLE   (TB$BTIME-TC$BTIME)/8760)*100   MOP #4  E(B YRS)
MOP4          FVARIABLE   (TB$BTIME*TC$BTIME)/8760)*140   EXP.ED # UNIT YRS OF B
              SAVEVALUE   097,V$MOP4,H            XH097 = E(OH)/V4*100 SIM TO THEORY
RATO1         FVARIABLE   (TB$ENOH/V4)*100
DIFF2         FVARIABLE   088,V$ENOH/V4*100
RATO2         FVARIABLE   (V$MOP4/10-)/(TB$NBARB)
              SAVEVALUE   087,V$RATO2)*100        RATO2=XHO89=MOP #12
FILRT         FVARIABLE   (XHO77/XHO79)*10000     FILRT=B/M TIMES 10000, MOP #2
              SAVEVALUE   069,V4,H                XH170=V4
DIFF1         FVARIABLE   TB$ENOH-V4              CHECK ON DIFF 2 USEING ENOH T.
              SAVEVALUE   090,V$DIFF1,H
BARB          FVARIABLE   (XHO56/XHO59)*100       E(B) AT ARB PT IN TIME
              SAVEVALUE   96,V$BARB,H             XH96=E(B) AT AN ARB POINT IN TIME
              SAVEVALUE   95,TB$RDYRT,H           XH95=READY RATE TIMES 100
              SAVEVALUE   089,V$DIFF2,H
              SAVEVALUE   087,V$DIFF1,H
              SAVEVALUE   099,V$FILRT,H
              SAVEVALUE   091,TB$NUMC,H           SET XH91=XH73 = C
              SAVEVALUE   078,XHO98,H             SET XH78=XH98 = # B THIX RUN
```

```
        SAVEVALUE   092,XH076,H                                              SET XH92=XH76  = #REP IND THIS RUN      3360
        SAVEVALUE   093,XH075,H                                             SSET XH93=XH75  = # ORDS THIS RUN        3370
        SAVEVALUE   078,XH098,H                                              SET XH78=XH98  = # B THIX RUN           3380
        SAVEVALUE   100,XH77,H                                               SET XH100=XH77 = E(#FILLS) THIS R       3390
        TEST E      94,TB$ENCH,H                                             MOP #7 E(OH) AT AN ARBPT IN TIME
        PRINT       XH5,0,JUMP                                               IF THERE IS AN ERROR.GET STD OUTPUT    3400
        TERMINATE                                                            IF STD OUTPUT IS REQ.ED SEND XA JMP
JUMP    PRINT       XH17,0,JUMP
        PRINT       5,100,XH,D
        PRINT       ,,,T                                                                                            3404
        PRINT       ,,,G                                                                                            3450
        PRINT       ,,,B                                                                                            3451
        PRINT       ,,,C
        TERMINATE   ,,,Q

*
        GENERATE    87600                                                    INCREMENT R BY ONE                     3460
        SAVEVALUE   2+,1,H                                                                                          3470
        TERMINATE   1-1,H                                                                                           3480
NBARB   TABLE       XH054,0,100,25                                                                                  3490
RDYRT   TABLE       XH044,0,100,3                                            TB OF TABLE = READY RATE, MOP #9       3500
NUMC    TABLE       XH53,0,100,25                                                                                   3510
BTIME   TABLE       XH05,8,-500,500,25                                       BORD TIMES                             3520
BTCHZ   TABLE       XH047,50,50,25                                           BTCH SIZE                              3530
FASTR   STORAGE     XH048,1,1,25                                                                                    3540
ORDER   STORAGE     99999                                                                                          3550
SLOWR   STORAGE     99999                                                                                          3560
        START       99999                                                                                          3570
        REPORT      1                                                                                               3580
SAV     SPACE                                                                                                       3590
        TITLE       30,I. SAVEVALUES (SYSTEM PARAMETERS & STATISTICS)                                               3600
SAV     SPACE
        TITLE       5,I.
10      SPACE
        TEXT        5,A. CLOCK TIME WHEN STATISTICS WERE GATHERED.
RUN SIMULATES SPACE  2,#X1.2/XXXXX# = THE NUMBER OF HOURS OF OPERATION THIS C
        TITLE
HSAV    SPACE
        TITLE       30, B. CRITICAL SYSTEM PARAMETERS.
10      SPACE
        TEXT        Q,ORDER QUANTITY      = #XH1,2/XXX#
10      SPACE
        TEXT        R,REORDER POINT       = #XH2,2/XXX#
10      SPACE
        TEXT        K,MAXIMUM BATCH SIZE  = #XH4,2/XXX#
10      SPACE
        TEXT        L,MINIMUM BATCH SIZE  = #XH3,2/XXX#
```

```
        HSAV
        SPACE  3
        TITLE  30,    C.  MEASURES OF PERFORMANCE, (MOP).
        SPACE  3
 10     TEXT   MOP  1 = #XH100,2/XXXXX#  ,  EXP NUM OF FILLS.
        SPACE
 10     TEXT   MOP  2 = #XH99,2/2LXX.XX#%  .  FILL RATE
        SPACE
 10     TEXT   MOP  3 = #XH98,2/XXXX#  ,  EXP NUM OF BACKORDERS.
        SPACE
 10     TEXT   MOP  4 = #XH97,2/2LXX.XX#  ,  EXPECTED NUMBER OF UNIT C
        TEXT   YEARS OF BACKORDERS PER UNIT PERIOD (10 YRS)
        SPACE
 10     TEXT   MOP  5 = #XH96,2/2LXX.XX#  ,  EXP NUM OF BACKORDERS ATC
        TEXT   AN ARBITRARY POINT IN TIME.
        SPACE
 10     TEXT   MOP  6 = #XH95,2/2LXXX.XX#%,  READY RATE, THE PROBABILC
        TEXT   ITY OF A FILL.
        SPACE
        TEXT   AT AN ARBITRARY POINT IN TIME.
        SPACE
 10     TEXT   MOP  7 = #XH94,2/2LXXX.XX#  .  EXP NUMBER OH-HAND (OH) C
        TEXT   IN TIME.
        SPACE
 10     TEXT   MOP  8 = #XH93,2/XXXX#  .  EXP NUM OF ORDERS PLACED.
        SPACE
 10     TEXT   MOP  9 = #XH92,2/XXXXX#  ,  EXP NUM OF REP INDUCTIONS
        SPACE
 10     TEXT   MOP 10 = #XH91,2/2LXX.XX#  ,  EXP NUM IN REPAIR (C) AT C
        TEXT   AN ARBITRARY POINY IN TIME.
        SPACE
 10     TEXT   MOP 11 = #XH90,2/2LXXX.XX#  ,  DIFF1 OH(SIM)-OH(THEORY)
        SPACE
 10     TEXT   MOP 12 = #XH89,2/2LXXX.XX#  ,  DIFF2 MOP4(S)-MOP5(SIM)
        SPACE
 10     TEXT   MOP 13 = #XH88,2/XXXXX.XX#%,RATIO1 OH(SIM)/OH(THEORY)
        SPACE
 10     TEXT   MOP 14 = #XH87,2/XXXX#%  ,  RATIO2 MOP4(S)/MOP5(S).
        SPACE
        TITLE  4,II.  STORAGE STATISTICS.
        SPACE
        STO
        TITLE  2.     A.  STATISTICS FOR ORDER DEPARTMENT.
        SPACE
        STO
        TITLE  1.     B.  STATISTICS FOR FAST REPAIR PROCESS.
        (INFINITE SERVER QUEUE REPAIR SYSTEM).
        SPACE
        STO
        TITLE  3.     C.  STATISTICS FOR SLOW REPAIR PROCESS.
        (FINITE SERVER QUEUE REPAIR SYSTEM)
        SPACE
        QUE
        TITLE  3,III.  QUEUE STATISTICS.
        SPACE
```

```
QUE     TITLE   1,   A.   STATISTICS FOR REPAIR DEP (INFINTE SYSTEM).
        SPACE
QUE     TITLE   2,   B.   STATISTICS FOR REPAIR DEPT (FINITE SYSTEM).
        END
```

3610

APPENDIX D SUMMARY AND STANDARD OUTPUT

CONTENTS OF HALFWORD SAVEVALUES (NON-ZERO)
SAVEVALUE

NR.	VALUE	NR.	VALUE	NR.	VALUE	NR.	VALUE	NR.	VALUE	NR.	VALUE	NR.	VALUE	NR.	VALUE
10	904	6	240	7	768	8	388	9	168	10	504	11	95	12	10
39	446	14	1	15	10000	16	685	35	1366	36	268	37	153	18	754
56	1866	43	828	44	100	45	1	46	685	47	153	49	1	53	400
76	1366	57	1366	58	685	59	1513	69	71	70	4	73	4	75	1
91	528	77	828	78	15	79	73	87	105	88	101	89	5	90	1
99	5472	92	828	93		94		95	5384	96	110	97	1157	98	685

I. SAVEVALUES (SYSTEM PARAMETERS & STATISTICS)

A. CLOCK TIME WHEN STATISTICS WERE GATHERED.

   87600 = THE NUMBER OF HOURS OF OPERATION THIS RUN SIMULATES

B. CRITICAL SYSTEM PARAMETERS.

   Q,ORDER QUANTITY   = 10

   R,REORDER POINT   = 2

   K,MAXIMUM BATCH SIZE =   1

   L,MINIMUM BATCH SIZE =

C. MEASURES OF PERFORMANCE, (MOP).

   MOP 1 =   828   , EXP NUM OF FILLS.

   MOP 2 = 54.72% , FILL RATE

   MOP 3 =   685   , EXP NUM OF BACKORDERS.

   MOP 4 = 11.57 , EXPECTED NUMBER OF UNIT YEARS OF BACKORDERS PER UNIT PERIOD (10 YRS)

   MOP 5 = 1.10   , EXP NUM OF BACKORDERS ATAN ARBITRARY PCINT IN TIME.

   MOP 6 = 53.84%, READY RATE, THE PROBABILITY OF A FILL.

MOP 7 = .73 , EXP NUMBER OH-HAND (OH) AT AN ARBITRARY POINT IN TIME.

MOP 8 = 15 , EXP NUM OF ORDERS PLACED.

MOP 9 = 1366 , EXP NUM OF REP INDUCTIONS

MOP 10 = 5.28 , EXP NUM IN REPAIR (C) AT AN ARBITRARY POINY IN TIME.

MOP 11 = .01 , DIFF1 OH(SIM)-OH(THEORY)

MOP 12 = .05 , DIFF2 MOP4(S)-MOP5(SIM)

MOP 13 = 101.0 %,RATIO1 OH(SIM)/OH(THEORY)

MOP 14 = 105% , RATIO2 MOP4(S)/MOP5(S).

II. STORAGE STATISTICS.

A. STATISTICS FOR ORDER DEPARTMENT.

STORAGE	CAPACITY	AVERAGE CONTENTS	AVERAGE UTILIZATION	ENTRIES	AVERAGE TIME/TRAN	CURRENT CONTENTS	MAXIMUM CONTENTS
ORDER	99999	.086	.000	15	508.066		1

B. STATISTICS FOR FAST REPAIR PROCESS. (INFINITE SERVER QUEUE REPAIR SYSTEM).

STORAGE	CAPACITY	AVERAGE CONTENTS	AVERAGE UTILIZATION	ENTRIES	AVERAGE TIME/TRAN	CURRENT CONTENTS	MAXIMUM CONTENTS
FASTR	99999	5.226	.000	1366	335.171	4	15

C. STATISTICS FOR SLOW REPAIR PROCESS. (FINITE SERVER QUEUE REPAIR SYSTEM)

III. QUEUE STATISTICS.

A. STATISTICS FOR REPAIR DEP (INFINTE SYSTEM).

QUEUE	MAXIMUM CONTENTS	AVERAGE CONTENTS	TOTAL ENTRIES	ZERO ENTRIES	PERCENT ZEROS	AVERAGE TIME/TRANS	$AVERAGE TIME/TRANS	TABLE NUMBER	CURRENT CONTENTS
FSTRQ	0	.000	1366	1366	100.0	.000	.000		

$AVERAGE TIME/TRANS = AVERAGE TIME/TRANS EXCLUDING ZERO ENTRIES

B. STATISTICS FOR REPAIR DEPT (FINITE SYSTEM).

END

STANDARD OUTPUT ONLY

TABLE BTIME
ENTRIES IN TABLE 685 MEAN ARGUMENT 148.417 STANDARD DEVIATION 92.625 SUM OF ARGUMENTS 101666.000 NON-WEIGHTED

UPPER LIMIT	OBSERVED FREQUENCY	PER CENT OF TOTAL	CUMULATIVE PERCENTAGE	CUMULATIVE REMAINDER	MULTIPLE OF MEAN	DEVIATION FROM MEAN
0	120	17.51	17.5	82.4	.336	-1.062
50	122	17.81	35.3	64.6	.673	-.522
100	127	18.54	53.8	46.1	1.010	-.017
150	117	17.08	70.9	29.0	1.347	.556
200	85	12.40	83.3	16.6	1.684	1.096
250	69	10.07	93.4	6.5	2.021	1.636
300	35	5.10	98.5	1.4	2.358	2.176
350	10	1.45	100.0	.0	2.695	2.716
400						

REMAINING FREQUENCIES ARE ALL ZERO

TABLE NBARB
ENTRIES IN TABLE 169 MEAN ARGUMENT 110.059 STANDARD DEVIATION 205.437 SUM OF ARGUMENTS 18600.000 NON-WEIGHTED

UPPER LIMIT	OBSERVED FREQUENCY	PER CENT OF TOTAL	CUMULATIVE PERCENTAGE	CUMULATIVE REMAINDER	MULTIPLE OF MEAN	DEVIATION FROM MEAN
0	109	64.49	64.4	35.2	.008	-.048
1000	14	8.28	72.7	27.2	.008	-.048
2000	18	10.61	83.4	16.5	1.817	.917
3000	10	5.91	89.3	10.6	2.725	2.424
4000	7	4.14	93.4	6.5	3.634	3.384
5000	4	2.36	95.8	4.1	4.543	3.684
6000	3	1.77	97.6	2.3	5.451	4.718
7000	0	.00	97.6	2.3	6.360	5.358
8000	2	1.18	98.8	1.1	7.268	6.177
9000	0	.00	98.8	1.1	8.177	6.846
10000	0	.00	98.8	1.1	9.086	7.331
11000	1	.59	99.4	.5	9.994	8.818
12000	0	.00	99.4	.5	10.903	9.305
13000	1	.59	100.0	.0	11.811	5.792

REMAINING FREQUENCIES ARE ALL ZERO

101

TABLE NUMC
ENTRIES IN TABLE 169   MEAN ARGUMENT 528.993   STANDARD DEVIATION 216.375   SUM OF ARGUMENTS 89400.000   NON-WEIGHTED

UPPER LIMIT	OBSERVED FREQUENCY	PER CENT OF TOTAL	CUMULATIVE PERCENTAGE	CUMULATIVE REMAINDER	MULTIPLE OF MEAN	DEVIATION FROM MEAN
0	3	1.77	.5	99.4	.189	-.444
1000	12	7.10	2.3	97.6	.378	-.982
2000	29	17.15	9.4	90.5	.567	-1.058
3000	23	13.60	19.5	80.4	.756	-1.596
4000	31	18.34	36.2	63.7	.945	-1.531
5000	16	9.46	56.2	43.7	1.134	-1.328
6000	16	9.46	74.4	25.5	1.323	-1.790
7000	6	3.55	84.0	15.9	1.512	-2.252
8000	3	1.77	91.7	8.2	1.701	-1.714
9000	0	.00	97.0	2.9	1.890	-1.638
10000	1	.59	98.8	1.1	2.079	-2.101
11000	1	.59	99.4	.5	2.268	-3.101
12000	1	.59	100.0	.0	2.457	-3.563
1300						

REMAINING FREQUENCIES ARE ALL ZERO

TABLE ENOH
ENTRIES IN TABLE 169   MEAN ARGUMENT 73.964   STANDARD DEVIATION 372.000   SUM OF ARGUMENTS 12500.000   NON-WEIGHTED

UPPER LIMIT	OBSERVED FREQUENCY	PER CENT OF TOTAL	CUMULATIVE PERCENTAGE	CUMULATIVE REMAINDER	MULTIPLE OF MEAN	DEVIATION FROM MEAN
-5000	0	.000	.00	100.0	-67.599	-.644
-4500	0	.000	.00	100.0	-60.839	-.639
-4000	0	.000	.00	100.0	-54.080	-.295
-3500	0	.000	.00	100.0	-47.319	-.951
-3000	0	.000	.00	100.0	-40.559	-.607
-2500	0	.000	.00	100.0	-33.799	-.263
-2000	0	.000	.00	100.0	-27.039	-.919
-1500	0	.000	.00	100.0	-20.279	-.575
-1000	2	1.18	1.1	98.8	-13.520	-.231
-500						-2.887
500	9	5.32	6.5	93.4	-.760	-1.542
1000	67	39.64	46.1	53.8	.000	-1.198
5000	77	45.56	91.7	8.2	6.760	-1.145
	14	8.28	100.0	.0	13.520	-2.485

REMAINING FREQUENCIES ARE ALL ZERO

TABLE RDYRT
ENTRIES IN TABLE 169   MEAN ARGUMENT 5384.613   STANDARD DEVIATION 4992.000   SUM OF ARGUMENTS 910000.000   NON-WEIGHTED

UPPER LIMIT	OBSERVED FREQUENCY	PER CENT OF TOTAL	CUMULATIVE PERCENTAGE	CUMULATIVE REMAINDER	MULTIPLE OF MEAN	DEVIATION FROM MEAN
0	78	46.15	46.1	53.8	1.000	-1.078
1000	91	53.84	100.0	.0	1.857	-.924

REMAINING FREQUENCIES ARE ALL ZERO

CURRENT MEMBERS OF GROUP   1
TRANSACTION MODE

BLOCK COUNTS			BLOCK	CURRENT	TOTAL	BLOCK	CURRENT	TOTAL	BLOCK	CURRENT	TOTAL	BLOCK	CURRENT	TOTAL
BLOCK	CURRENT	TOTAL												
1	0	1	11	0	2	21	0	1513	31	0	617	41	0	613
2	0	151	12	0	1513	22	0	1498	32	0	1362	42	0	613
3	0	151	13	0	1366	23	0	1366	33	0	1362	43	0	685
4	0	151	14	0	1366	24	0	1366	34	0	1362	44	0	1226
5	0	151	15	0	617	25	0	1366	35	0	1362	45	0	1524
6	0	151	16	0	617	26	0	1366	36	0	1366	46	0	1
7	0	151	17	0	1234	27	0	1366	37	0	617	47	0	1
8	0	151	18	0		28	0	1366	38	0	617	48	0	1
9	0	2	19	0		29	0	1366	39	0	613	49	0	1
10	0	1	20	0		30	0	1366	40	0	613	50	0	1
51	0	1	61	0		71	0	3629	81	0	685	91	0	685
52	0	1	62	0		72	0	177	82	0	685	92	0	685
53	0	1	63	0		73	0	79	83	0	685	93	0	685
54	0	1	64	0		74	0	79	84	0	685	94	0	685
55	0	1	65	0		75	0	79	85	0	685	95	0	685
56	0	1	66	0		76	0	749	86	0	685	96	0	685
57	0	1	67	0		77	0	749	87	0	685	97	0	685
58	0	1	68	0		78	0	749	88	0	685	98	0	685
59	0	0	69	0		79	0		89	0	685	99	0	0
60	0	0	70	0		80	0		90	0	685	100	0	0
101	0	0	111	0	1	121	0	0	131	0	0	141	0	169
102	0	0	112	0	1	122	0	0	132	0	0	142	0	169
103	0	0	113	0	1	123	0	0	133	0	0	143	0	169
104	0	0	114	0	1	124	0	0	134	0	0	144	0	169
105	0	0	115	0	1	125	0	0	135	0	0	145	0	91
106	0	0	116	0	1	126	0	0	136	0	0	146	0	78
107	0	0	117	0	1	127	0	0	137	0	0	147	0	1
108	0	0	118	0	1	128	0	0	138	0	0	148	0	169
109	0	0	119	0	1	129	0	0	139	0	0	149	0	1
110	0	0	120	0	1	130	0	0	140	0	0	150	0	
151	0	1	161	0	1	171	0	1	181	0	1			
152	0	0	162	0	1	172	0	1	182	0	1			
153	0	1	163	0	1	173	0	1	183	0	0			
154	0	1	164	0	1	174	0	1	184	0	0			
155	0	1	165	0	1	175	0	1	185	0	1			
156	0	1	166	0	1	176	0	0	186	0	1			
157	0	1	167	0	1	177	0	0	187	0	0			
158	0	1	168	0	1	178	0	1						
159	0	1	169	0	1	179	0	1						
160	0	1	170	0	1	180	0	0						

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13. ABSTRACT

A probabilistic event-step computer simulation of a repairable item inventory system with exponential inner-arrival times between demands is constructed. The model allows for a wide variety of repair times and lead times to be considered. The major parameters are investigated for their sensitivity to system changes in order to help the user evaluate given or proposed inventory policies and parameters. A complete description of the model is presented and various measures of supply performance such as the expected number of unit years of backorders per unit period and the fill rate are provided. All flow charts and the GPSS/360 program listing are included.

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